# A PAPER TO BE PRESENTED AT THE A.A.A.S. MEETING IN BERKELEY

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Speaker: Dr. Bart J. Bok, Harvard College Observatory

Topic: THE NEW SCIENCE OF RADIO ASTRONOMY

------ Address of the Retiring Vice-President ------

of Section D

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One of the prerogatives of a Vice-President of a Section of the AAAS is that, upon his retirement from office, he is given the opportunity to address his colleagues in his own and related fields upon a general topic of his choosing. I shall discharge this responsibility tonight by surveying with you the accomplishments to date and some prospects for the future in the new science of Radio Astronomy. The field may be a young one, but it has for the past ten years been a very active one, and I can hardly be expected to cover it in all its aspects in one single lecture. What I propose to do tonight is to highlight certain current trends and achievements and to omit, without apologies, others intrinsically fully as worthy of our consideration. To save time, I shall not speak tonight at all about the borderline fields of combined studies of the ionosphere and radio astronomy, and I shall further not consider the broad new field of radio studies of meteors, in which A. C. B. Lovell and his associates in Manchester, England, and P. M. Millman and D. W. R. McKinley in Ottawa, Canada, have made such remarkable advances. Tonight we shall concern ourselves briefly with radio observations of the sun, with studies of the general galactic background and discrete sources, and, in somewhat more detail, with current research in the field of radio radiation at 21-cm wavelength that reaches us from the neutral hydrogen clouds of our own Milky Way System.

It is well that we should note at the start that before the advent of radio astronomy, all of our knowledge of the physical universe of stars and galaxies had been obtained from analyses of a relatively narrow range of wavelengths. Until a few years ago, it was not possible, because of atmospheric absorption, to study by optical methods radiations from the sun and stars with wavelengths less than 3,000A. Rocket research has made it possible to send relatively simple apparatus to high altitudes and thus obtain observations in the violet to 1,000A, but we shall probably have to wait for the days of the "space platform" before we shall be able to make extensive studies of this radiation. Thermocouples and other heat-measuring devices -- as well as remarkable developments in infrared-sensitive photographic emulsions -- have made it possible to reach beyond the visible red spectrum into the heat spectrum, but our earth's atmosphere absorbs radiation so heavily in these regions that relatively little information has been obtained concerning radiations with wavelengths in excess of 30,000A. Our basic range of available frequencies for optical research does not extend much beyond the 1,000 to 30,000A range, which means that most of our knowledge about the universe has come from studies of not more than five octaves of the electromagnetic spectrum. Since the first discovery of radio radiation from the Milky Way in 1931 by Karl G. Jansky of the Bell Telephone Laboratories, it has been found that radio radiation can actually be recorded for the entire range of wavelengths between one centimeter and 30 meters, a total range of roughly twelve octaves of the electromagnetic spectrum.

To record and study the radio radiation reaching us from outer space, we require very large antennas and sensitive electronic recording apparatus. Let us first consider briefly the antenna problem. In our first course in optics, we learn that the performance of a mirror depends upon the size of the mirror and on the precision of its surface. Optimum performance can generally be guaranteed if the mirror's surface agrees to within one-quarter wavelength with the desired geometrical figure. Size of the mirror is important in two ways, since it controls not only the limiting brightness for the faintest object within reach, but also because the linear size of the mirror determines the smallest angular detail that one may hope to resolve. For radio studies, we require large paraboloid antennas, first of all because the radio radiation is weak and we need to squeeze all we can get into a small point at the focus; and second, because the angular resolution of a paraboloid antenna depends only upon the aperture of the antenna expressed in terms of the wavelength of the radiation that one studies. A 60-foot antenna used for the study of the 21-cm radiation from our galaxy will only resolve detail in surface features of the order of a little less than one degree. Since one-quarter wavelength is here about equal to two inches, the tolerances of the reflector's surface in all positions should not exceed this amount.

The need for large antennas was first realized clearly by the pioneer investigator Grote Reber, who, in 1937, and with very little outside support, built at his home in Wheaton, Illinois, a 31-foot parabolic antenna. The largest radio mirror now in operation in the United States is the 50-foot paraboloid of the Naval Research Laboratory in Washington, D.C. With the support of the National Science Foundation, Harold I. Ewen and I and our associates at the

Agassiz Station of Harvard Observatory are undertaking the construction of a 60-foot steerable antenna. Two larger parabolic antennas are now being built, one a 75-foot paraboloid for use by the Dutch radio astronomers, the other the giant 250-foot paraboloid for the Jodrell Bank Station of the University of Manchester in England. Let me say right here that I do not wish to give the impression that large paraboloids are the one and only solution to all problems in radio astronomy. But before we return to problems of instrumentation, let us first consider briefly how far the science of radio astronomy has advanced to date in its several departments.

## The Radio Sun

The sun was not discovered as a source of radio radiation until 1942, and the detection of the radiation at that time, coming as it did almost as a by-product of wartime radar research, may almost be termed accidental. The art of electronics has, however, advanced so rapidly over the past fifteen years that that the radio sun now represents one of the most accessible objects for study over the entire range of wavelength. It is an exceedingly strong emitter at wavelengths of the order of half a meter and greater, but even at a shorter wavelength its radiation is sufficiently strong to permit at present careful and detailed study. The radiation output of the sun in the radio range is far from constant. We recognize that the lowest level of radiation output at most wavelengths is that of the "quiet sun", and it has indeed been fortunate that careful studies of the radiation base have been made during the unusually peaceful minimum of activity in the 11-year solar cycle through which we have just passed. At times of solar activity, all sorts of disturbances occur that produce enhanced radio radiation of the sun.

Now that we are gradually moving toward an increase in all kinds of solar activity associated with the 11-year cycle, we may expect to observe with growing frequency the radio "noise storms" that accompany the passage of large sunspot groups across the solar disk. "Radio outbursts" and "isolated bursts", some of them associated with visible solar flares, others without any visible means of support, should again become the order of the day. Perhaps the most striking aspect of this variable solar radiation at radio wavelengths is the extreme range of its variability, which, at some wavelengths, may amount to a factor as great as one million. This variability is far greater for meter wavelengths than for wavelengths of 50 cm and less.

We have known for many years that variability of the sun's radiation has important effects upon the earth, especially upon the atmosphere of the earth. It now appears that in the records of variation of radio radiation from the sun, we have potentially one of the finest barometers for the study of solar variability. Since new and refined techniques of observation have become available in recent years, it is now possible to localize the sources of specific disturbances on the sun's surface or in its atmosphere. Through the combined study of radio and optical effects, we may hope to gain insight into the origin of these disturbances, and, from these, in turn, should follow an approach to an understanding of their effects upon the earth and its atmosphere. At several radio observatories, the study of the radio sun is now the primary research project. Outstanding work is currently being done at the radio observatory in Sydney, Australia; at the two major radio centers in Great Britain, Manchester and Cambridge; at the Naval Research Laboratory and Cornell University in the

United States; by A. E. Covington in Canada; and by groups in France, Belgium, and Japan. The most revolutionary apparatus has been built in Australia under the direction of E. G. Bowen and J. L. Pawsey. W. N. Christiansen and his associates are operating near Sydney two very high-resolution interferometer arrays of small radio mirrors, and J. P. Wild and his group have a rapidly scanning radio spectrometer. The Christiansen apparatus permits the very precise localizing of sources of excess radio radiation on the sun, and with the Wild apparatus one obtains an almost continuous picture of the brightness distribution in frequency of any disturbance on the sun.

At wavelengths of the order of one meter and greater, the sun is subject to terrific variations in radio brightness. The radio radiation in the meter-wavelength range is produced mostly in the sun's corona, and the radiation from the quiet sun is already sufficiently strong to be indicative of temperatures in the million-degree range in these outer parts of the sun's atmosphere. Increases in the noise level of the sun by a factor of one thousand over that of the quiet sun have been observed, and here one should bear in mind that quite often the increase can apparently be localized on small areas in the sun's atmosphere. It seems most unlikely that this enhanced solar radiation is of thermal origin. The coming sunspot maximum promises a gradual increase in activity in the radio range, and with the new equipment now at hand, great advances in interpretation of solar radio phenomena are bound to come within the next decade.

At the shorter wavelengths, the sun is a relatively constant radiator and here more and more attention is being given to the study and interpretation of brightness distribution over the disk. All sorts of techniques have been employed to study the variation of brightness with distance from the center of the sun's disk. In Great Britain, at Cambridge and at Manchester, interferometric studies showed some time ago that the sun's surface appears to be of by no means uniform brightness. Furthermore, eclipse observations had shown that some of the radiation reaching us comes from well above the layers of the photosphere, from the upper chromosphere and even the lower corona; John P. Hagen and Fred T. Haddock at the Naval Research Laboratory in Washington have done some of the finest work in this field.

Until a few months ago, it seemed that there would at least be radial symmetry in the brightness distribution over the sun's surface. This illusion has been rudely shattered by the recent provisional results announced by W. N. Christiansen and his associates. Evidence now exists that at wavelengths near 21 cm, the continuous radiation of the sun varies in quite a different fashion along the sun's equator than along a radius from center to pole. It will be exceedingly interesting to watch developments in the years to come and to see to what extent the character of these variations with latitude on the sun remain unchanged during the coming period of increased solar activity.

## Discrete Sources and Continuous Background

The first complete surveys of the radio radiation from the Milky Way and beyond were those begun in 1939 and completed in the early 1940's by Grote Reber. After the war, in 1947, J. S. Hey, J. W. Phillips and S. J. Parsons in Great Britain published a sky survey at 4.7 meters wavelength. Several others have been made since then, notably the recent one, at 120 cm wavelength, by J. D. Kraus at Ohio State University. In all of these surveys, the band of the Milky Way appears as the most clearly marked phenomenon, and the great strength of the radio radiation reaching us from the direction of the center of our galaxy is a characteristic feature of all isophotic maps. In addition to the radiation attributable to some variety of discrete source or sources of radio radiation associated with our Milky Way System, we observe a general background component coming to us presumably from far beyond the borders of our own galaxy. Other galaxies combine to produce much of this background component, and Kraus has shown that there is evidence for radiation from clusters of galaxies -- possibly originating in part in the spaces between the galaxies.

We are beginning to understand the origin of the continuous radiation from our own galaxy at centimeter wavelengths. The studies by J. P. Hagen and F. T. Haddock and their associates at the Naval Research Laboratory in Washington have revealed that enhanced continuous radiation reaches us from the direction of some of the best-known optical emission nebulae. This radiation almost surely comes from free-free transitions in ionized hydrogen clouds and, even before it had been observed, its presence had been predicted by J. L. Greenstein of the California Institute of Technology. The chief puzzle that remains today is just why this radiation at wavelengths of 50 cm and less should be so very strong from the general direction of the center of our galaxy, since off-hand we do not associate excessive amounts of ionized hydrogen with the nuclear regions of galaxies. The discovery by the NRL group of one or more strong discrete sources at centimeter wavelengths in precisely the direction of the galactic center shows that ionized hydrogen does exist near or at the center of our galaxy. Perhaps our galaxy has something in common with the galaxies studied several years ago by C. K. Seyfert and R. Minkowski, who noted the presence of strong emission lines near the centers of several galaxies; this observation suggests that conditions near the center of these galaxies are not unfavorable for the production of radio radiation by free-free transitions.

There are at present several theories to explain the origin of the continuous radiation at meter wavelengths, but to date none of them seems really satisfactory. Thermal radiation of the type we suspect at shorter wavelengths cannot be considered the principal source, since the brightness temperatures for the continuum in the meter range point to equivalent black-body temperatures of the order of one million degrees Kelvin, far in excess of known interstellar temperatures, which do not rise much above 10,000° K. The origin of continuous radiation in the meter range is at present sought mostly in an agglomeration of thousands upon thousands of faint "radio-stars", or at least in discrete and relatively small sources, distributed somewhat in the manner of the stars of Population II (though <u>not</u> the known optical stars of Population II). These suggestions have considerable merit but they do not really go to the heart of the problem, since we have as yet no inkling as to the manner in which these discrete sources manage to radiate with such tremendous vigor in the radio range.

I must, alas, be brief in my references to the <u>Discrete Radio Sources</u>. The discovery of these discrete emitters of radio radiation was forshadowed by the work of Hey, Phillips and Parsons, to which we have already referred, who found indications for a strongly emitting source in Cygnus. The Australian scientists J. G. Bolton and G. J. Stanley not only confirmed the presence of the discrete source in Cygnus, but they succeeded in measuring (1948) its diameter with accuracy. This was done with the aid of the sea interferometer. Following these first studies, the field developed rapidly with the discovery of many fainter sources. In Great Britain, M. Ryle and his associates D. D. Vonberg and F. G. Smith in Cambridge, and R. Hanbury Brown and associates at Jodrell Bank, had developed other interferometer techniques; at the same time Hanbury Brown had constructed his fixed 218-foot paraboloid. Bernard Mills in Australia extended the earlier surveys, and he and Smith measured with high precision the positions of the brightest discrete sources. In the past few years, research on discrete sources has developed beyond the dreams of all but the most venturesome. Ryle and his associates have built a beautiful interferometer array, with four major components with a light-gathering power (in Ryle's words) "of one acre", which promises to yield soon a published list of 1750 specific discrete sources. In Australia, Mills is operating an even more revolutionary type of instrument, the Mills Cross, which produces a pencil beam subtending a very small solid angle.

A wholly new series of problems presents itself when we turn to the identification of the discrete radio sources with optically observed objects. We might readily devote a whole evening to this fascinating topic, but that sort of lecture should be given by Dr. R. Minkowski or by Dr. W. Baade, of the Mount Wilson and Palomar Observatories, without whose researches on the subject we would today still be floundering in ignorance. The most striking fact discovered is that very few of the conspicuous stars and nebulae of our Milky Way System are among the recognized objects in the radio sky. The brightest discrete source within our Milky Way System is that in Cassiopeia, which has at its position in the sky some highly turbulent emission nebulosity, which is far from striking even on the Palomar Schmidt photographs. The brightest discrete source that is placed outside our Milky Way System is that in Cygnus; it results apparently from the collision between two galaxies, presumably about 200 million light years away! Number 3 on the list is an old acquaintance, the Crab Nebula in Taurus, the product of an ancient supernova explosion and now a highly turbulent gas mass. Other sure identifications are mostly with single galaxies, some of which have highly peculiar features; pairs of galaxies in collision, or at least interacting with each other; and groups of galaxies.

The definite identification of a discrete source presents very difficult problems to the optical astronomer and the radio astronomer alike. In many cases the optical manifestation corresponding to a discrete source at radio wavelengths is elusive and faint and very difficult to observe. Since we are dealing with optically very weak objects, we must have very accurate positions for the discrete sources before we can hope to start work on the identification. At present the required accuracy is lacking for all but the brightest radio sources and the problem is further complicated by the "ghosts" of radio astronomy, the side-lobes of instrumental patterns that often confuse the radio astronomer. The application of widely differing techniques for the detection of discrete radio sources is highly desirable, since the pattern of side-lobes is very different for Ryle's wonderful multiple interferometer, for the Mills Cross, and for Kraus' knife-edge antenna with its helices. By the use of a variety of techniques, and with everlasting emphasis on high precision in the measurement of positions, we may count on slow future progress in identification, but the path will at best be one difficult to travel.

## The 21-cm Line of Neutral Hydrogen

The first phase in the development of a new branch of science is often one in which single spectacular discoveries are made, every one of them of real value for its own sake, but most of them not intimately related to developments in neighboring areas of scientific research. In the second phase, the new science becomes an integral part of a group of related scientific fields and it contributes to the solution of scientific problems that are amenable to study by a variety of approaches. Radio astronomy is slowly passing from the first to the second phase. We are seeing this happen in solar research, where the radio data, properly blended with optical data, are providing us with a fresh approach to the study of solar activity, and are giving us new insight into conditions in the sun's atmosphere. In the meter wavelength range, the discrete radio sources are still an enigma, but identification with optical objects has progressed to the stage where we realize that we are here dealing with phenomena associated with highly turbulent gas masses. In the centimeter and decimeter range, radio and optical studies of emission nebulae are already proving to be different ways of studying the effects of free-free transitions in ionized gas clouds. In no other area, however, has the blending progressed so far as in the study of the 21-cm radiation from neutral hydrogen. The investigator of 21-cm features cannot possibly disentangle the confusion of his radio data without repeated reference to the results of optical research, and the time has apparently come in which the optical Milky Way astronomer must be thoroughly aware of the work of his colleagues in the radio field if he wishes to make headway in the interpretation of optical data.

The romantic story of the prediction and discovery of the 21-cm line of neutral hydrogen has now been told several times, but it bears repeating. In 1944, H. C. van de Hulst, of Leiden, Holland, predicted in a war-time astronomical colloquium in occupied Holland that it might be possible to detect the 21-cm radiation originating in the clouds of neutral hydrogen of our galaxy. This radiation was detected in March, 1951 -- less than four short years ago! -- by H. I. Ewen and E. M. Purcell of Harvard University, and their discovery was confirmed promptly by radio groups in Holland and in Australia. The radiation originates in a transition between the two hyperfine levels of the Lyman level of the neutral hydrogen atom; the energy of the hydrogen atom is slightly greater when the spins of the nucleus and the electron are parallel than when the spins are anti-parallel. The 21-cm line appears in emission as a result of transitions form the higher level of parallel spins to the lower level of anti-parallel spins; an absorption results from a transition in the opposite sense.

It is interesting to reflect that, before the days of 21-cm research, we had no ways of confirming by direct optical observation the existence of extended interstellar clouds of neutral hydrogen. It is true that the Balmer lines of neutral hydrogen are observed in emission in the spectra of most diffuse nebulae, but it has long been known that these emission lines result as a by-product of the recombination of a free electron and a proton; in a cloud of ionized hydrogen, a free electron is captured in one of the higher quantum number orbits of the neutral atom, and the just formed neutral atom has the excited electron cascading promptly to the lowest, or Lyman level, emitting a Balmer quantum on the way. The clouds of hydrogen in which these processes take place are basically clouds of ionized hydrogen, for there simply would no be enough excitation energy available in a predominantly neutral cloud to lift a perceptible fraction of the atoms to the levels with quantum numbers three or higher and thus permit emission of a Balmer quantum by the cascading process just described. The optical researches of Walter Baade of Mount Wilson and Palomar Observatories, and of W. W. Morgan and his associates at Yerkes Observatory, had already shown conclusively that the clouds of ionized hydrogen are observed only along the spiral arms of galaxies and, while one could surmise that the neutral hydrogen clouds would fill the remainder of the spiral pattern, no definite proof of this assumption could be given before the days of 21-cm research. This situation has changed as a consequence of recent radio-astronomical studies.

Three years ago, J. H. Oort and his associates began their epoch-making researches into the spiral structure of our own galaxy for the sections that can be studied from the northern latitude of Holland. They have found evidence for three clearly marked sections of major spiral arms; the first, known as the Orion arm, in which our sun is located; the second, the Perseus arm, so named after its most conspicuous stellar component, the double cluster in Perseus; and the third, an as yet unnamed arm still farther from the center of our galaxy than the Perseus arm. It should be noted that sections of the Orion arm and of the Perseus arm had already been discovered by Morgan and his associates, but the Dutch radio researches showed that the Perseus arm could probably be traced to well beyond the center of our galaxy. By optical methods, it had been found possible to detect traces of spiral structure in our own Milky Way System to distances from our sun to 3000 parsecs, and even a bit more, but no one could have dreamed before the days of 21-cm research that it would become possible to detect with relative ease elements of spiral structure of our own galaxy to distances as great as twelve to fifteen thousand parsecs from our sun. The secret of the success of the Dutch investigators lies in the fortunate circumstance that the dense dust clouds of our galaxy, which cut off our optical view of the more distnat elements of spiral structure, transmit undimmed the 21-cm radiation reaching us from great distances. In the course of the past year, the Australian radio astronomers F. J. Kerr and J. V. Hindman have extended the Dutch survey so that both the northern and southern hemispheres have now been studied. The preliminary map of spiral structure given by Kerr and Hindman supplements the picture provided for us by the Dutch group, and shows conclusively that there is much spiral-like structure in our own galaxy at distances from the galactic center between 20,000 and 40,000 light years, that is, for distances from the galactic center comparable to the distance from our sun to the center. Considerable neutral hydrogen is also present in the inner parts of our galaxy, but here further detailed studies -- preferably to be undertaken with radio telescopes of far greater aperture than those available at the present time -- are required before the complex central structure may be disentangled.

During the next few years it should be possible to study from carefully planned regional surveys the detailed features of the spiral structure of our galaxy. The Dutch radio astronomers have already undertaken a second survey in which the centers for the study of the 21-cm line are much more closely spaced than in the first survey. Detailed regional surveys are now in progress at the Agassiz Station of Harvard Observatory and at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. Thomas A. Matthews who has been observing at the Agassiz Station, has just presented at this meeting the first results showing the detailed spiral structure of our galaxy exhibited by the section of the Milky Way from Lacerta and Cepheus through Cassiopeia to Perseus. While there is evidence of considerable turbulent motion in the hydrogen clouds, there are also some marked cases of bifurcation of spiral arms. It is cheering to note that the groups and associations of hot stars -- which traditionally are found to follow very closely the spiral pattern of galaxies -- reveal indeed a pattern not unlike that of the neutral hydrogen. The small clouds that produce the remarkable multiple stellar absorption lines found by Guido Münch, of the California Institute of Technology, also fit very well into the structural pattern found by Matthews. At the Department of Terrestrial Magnetism L. Helfer and H. Tatel are engaged upon studies of a similar nature and there is good agreement between results of observations of centers in common between the several radio surveys.

In the regional surveys to which we have just referred, we find that the radio astronomer cannot analyse his material properly without constant reference to the results obtained by the older methods of optical astronomy and vice versa. This blending of the two techniques of optical and radio astronomy is perhaps seen equally well in the studies dealing with the gas constituent of large complexes of cosmic dust and the somewhat smaller clouds of dust known as dark nebulae. The problem of whether or not concentrations of cosmic dust are also proportionally great concentrations of interstellar gas has for some years loomed large in optical astronomy. It has become apparent from theoretical studies that the dust clouds of our Milky Way System may well mark locations where the formation of new stars is under way and it is obviously important to decide how much gas is present relative to the dust in one of these dense dark nebulae; the predicted course of evolution of a dark nebula is bound to be very dependent upon the answer to this question. It seemed impossible to settle this question by optical research, but through the new techniques of radio astronomy we seem to be heading toward a solution.

About a year ago, A. E. Lilley decided to use the Agassiz Station radio telescope in a study of the 21-cm radiation from the Taurus dark nebula complex and surroundings. He found that the strength of the 21-cm signal increased markedly as he measured, starting first at a position in the sky well outside the limits of the dark complex, and then gradually moving to positions closer to the apparent boundary of the complex, making sure at all times that his positions were spaced at a constant angular distance from the central band of our Milky Way. A signal of fairly uniformly high intensity was then received from all positions at comparable distance from the galactic circle inside the complex, but Lilley found the signal to decrease again in strength as he passed to positions beyond the other edge of the complex. In other words, Lilley could show by his observations that the known concentration of cosmic dust in the complex is accompanied by a concentration of neutral hydrogen gas. So far, so good. But, we ask, do the very densest dark spots inside the dark nebulae complex exhibit the further increase in signal strength of the 21-cm radiation that one might expect, if gas and dust were found everywhere in precisely the same proportion? Lilley's results did not permit us to answer this question unequivocally and further special research was obviously necessary. The next step was taken by B. J. Bok, R. S. Lawrence, and T. K. Menon, who, again observing with the Agassiz Station radio telescope, compared the signal strength for two very dark centers in the Taurus complex and one very dark center in the

Ophiuchus complex with the signal strength of neighboring far less obscured areas of the sky. The result of this investigation, on which we reported at this meeting, confirms the preliminary result obtained last year by the Dutch radio astronomers: the very densest dark spots do not show the expected increase of 21-cm signal strength that should occur if cosmic dust and neutral atomic hydrogen were present everywhere in the same proportions. In future studies we shall have to consider more seriously than we have in the past the probable evolutionary development of relatively small dark nebulae without a vary great gaseous component.

One might ask, why should we get so worked up about a possible gaseous admixture in our clouds of cosmic dust? The answer to this question is that the role that the gas plays in a dust complex as a whole is by no means very small. According to Lilley, the average value for the ratio between the density of the gas and that of the dust inside a complex is of the order of 100. The techniques of radio astronomy have provided us with a clear-cut answer to the problem of the presence of neutral atomic hydrogen in dark nebulae complexes and individual clouds of cosmic dust; there is an excess of neutral atomic hydrogen in the large complexes, but the densest spots of cosmic dust in the dark nebulae complex have no more than an average hydrogen gas content. There still remains with us, however, the problem that molecular hydrogen may be abundant, especially in the denstest small dark nebulae. For the present, neither radio nor optical techniques can give us any information regarding the presence or absence of molecular hydrogen, and for the time being, we shall have to return to pure theory and speculation in considering the pros and cons for interstellar hydrogen molecules.

A fascinating array of novel problems presents itself when we consider the 21-cm radiation that reaches us from the direction of the center of our galaxy. An extensive general survey of the 21-cm line profiles for the direction of the galactic center and the entire surrounding section has been made by D. S. Heeschen, again using the equipment at Agassiz Station. The observed profiles, in which the measured brightness temperature is plotted against frequency (which corresponds to radial velocity of approach or recession), show a simple Gaussian character for positions some degrees away from the precise direction of the galactic center, but for directions near that of the center, double-peaked curves appear, which indicate either contributions from multiple cloud systems, or self absorption caused by differences in temperature along the line of sight. This particular section of the Milky Way is being studied in great detail, and very effectively, by J. P. Hagen and his associates at the Naval Research Laboratory in Washington, D.C., where the great 50-foot antenna is in operation. The first important result was announced at the Boston meetings of the AAAS one year ago, when F. D. Haddock, C. H. Mayer and R. M. Sloanaker told of the discovery of a strong discrete source in the direction of the galactic center and observed at a wavelength of 9.4 cm. A few months later, Hagen, E. F. McClain and N. Hepburn studied the same region of the sky in the continuum just outside the 21-cm line and confirmed the presence of strong radiation from the precise direction of the center of our galaxy. During the past summer, McClain has investigated further the profile of the 21-cm line of the galactic center, using the highest resolution attainable. The result is a profile with several -- three at least -- remarkable absorption features, indicating the presence of several relatively small, but very dense, absorbing clouds of neutral hydrogen between our sun and the source of continuous radiation at the galactic center itself.

The studies by Hagen and his associates have raised the important question of possible absorption effects produced by small clouds of neutral hydrogen in the spectra of remote disctete sources of continuous radio radiation. The first very remarkable result has just been announced by Hagen, Lilley, and McClain. The famous discrete source in Cassiopeia, which is now readily dectable as an emitter of fairly strong continuous radiation in the vicinity of the 21-cm line, shows at the wavelength range of the 21-cm line three distinct and very sharp absorption features. These must be produced by small and compact, but very dense clouds of neutral hydrogen, reminiscent of the sharp absorption features noted by Guido Münch in his studies of the interstellar K and D lines by optical methods. With the discovery of these unusually sharp absorption features, Hagen and his group have opened up a new era in radio research.

Our present equipment is not yet sufficiently sensitive to detect the radiation of any of the galaxies ourside our own, with the exception of the two Magellanic Clouds. The Large and the Small Star Clouds of Magellan are too far south for northern hemisphere observers, but they are in excellent position for study from Sydney, Australia, where F. J. Kerr, G. F. Hindman and B. J. Robinson have investigated them with their 21-cm equipment. Before the Australian astronomers began their work, optical astronomers were pretty well agreed that the Large Magellanic Cloud is rich in hydrogen gas, but most of us supposed that there would be relatively little hydrogen in the Small Cloud. Kerr and his associates have demonstrated conclusively that atomic neutral hydrogen, as revealed by the 21-cm line, is abundant in both the Large and Small Clouds

The two Clouds are observed to be embedded in very large and bright massive clouds of neutral atomic hydrogen, with the total hydrogen content of the Small Cloud being only relatively little less than that of the Large Cloud.

I have purposely listed in considerable detail in the preceding paragraphs the most striking discoveries obtained to date from the study of the 21-cm spectrum line alone. The accomplishments in their considerable variety demonstrate the versatility of the new approach to the study of the interstellar medium. In considering these accomplishments we should keep in mind that four years ago we were still three months short of the original discovery by Ewen and Purcell. Already it has become virtually impossible for the Milky Way astronomer to think of his field of research without considering studies of the 21-cm radiation. The potentialities for future research are tremendous. For studies of our own Milky Way System, we stand to gain very much from the use of larger antennas to provide us with greater resolution in angle, and from further electronic developments.

The future detection and study of 21-cm radiation from the nearby galaxies and from the remote clusters of galaxies promises to yield some very useful basic information about these galaxies and the motions of the gases within them. The detection of inter-galactic neutral hydrogen which now presents a very difficult problem, becomes something to be dealt with in the future. We should remember at this point that up to the present time we have been dealing with only one single spectrum line, that near 21 cm. It is not impossible that other lines do exist, and the search for two of the most likely ones, the deuterium line at the frequency of 327 mgc/sec and the components of the OH band at 1667 mgc/sec, are on the high priority list.

## The Future of Radio Astronomy in the United States

It is my privilege today to address the most representative audience of scientists that gathers annually in the United States, the membership of the AAAS. It is therefore fitting that in closing I should review briefly the present state and future prospects of radio astronomy in the United States. Radio telescopes are now in operation in the United States at the Naval Research Laboratory and at the Department of Terrestrial Magnetism of the Carnegie Institution in Washington, D.C., and at the Agassiz Station of Harvard Observatory at Cornell University and at Ohio State University. The National Bureau of Standards has a program on the way, but I do not believe that I am doing anyone an injustice by saying that this about completes the picture. At present only three universities have graduate students in radio astronomy, and the total number of graduate courses in the field offered during the past year has not been more than five. Radio astronomy is a field in which success can be achieved only if astronomers, physicists, and electronic engineers work in continued close collaboration, and there are unfortunately very few institutions where collaboration of this sort is now in effect. This is certainly a meager showing for the Unites States in a field that holds as much promise as does the new radio astronomy.

Fortunately, the scientists of the United States who should concern themselves with radio astronomy are very much aware of the need for increased activity in this young field. Last year we had a very gratifying response to the AAAS Symposium on Radio Astronomy organized by Sections D and B. Early in January 1954 the National Science Foundation called together in Washington a three-day meeting of radio astronomers, established and potential, from the

United States, and invited to this meeting were some of the leaders from abroad. Much enthusiasm was expressed at the Washington Symposium for increased United States activity in radio astronomy, and the NSF has since then established a special Panel on radio astronomy. Under the able chairmanship of Merle A. Tuve, the Panel not only concerns itself with the judging of applications for financial support for the immediate future, but it has also as its primary assignment, the task of promoting the development of an effective effort in the field in the United States.

There is no denying that radio astronomy is an expensive science. If we wish to participate in research in the meter-wavelength range, we shall need to build equipment that has greater resolution in angle and permits settings with higher precision than is available today. A very large steerable paraboloid, or a fixed one, or instruments of very novel design may be the answer to some problems, but, since energy is plentiful at meter wavelengths, others can be solved more effectively through the use of interferometer or pencil-beam techniques. In the range of centimeter and decimeter wavelengths, we are looking mostly for instruments that will give increased angular resolution and that will at the same time gather more of the very weak radiations that reach us at these wavelengths. For the time being, large steerable paraboloid antennas seem to be the preferred instruments for the shorter wavelengths, but we should be aware of the possibility that improved electronic instruments may make it advisable to consider interferometric and pencil-beam techniques a year or so from now, not only for the long but also for the short waves. The end of major new developments in electronics is still not in sight. A considerable fraction of the funds available for the construction of a large radio observatory should therefore be set aside for research and development in electronic instrumentation.

The financial support for our existing American radio astronomy enterprises has come from a variety of sources, The principal contributors to the project in radio astronomy at Agassiz Station have been the National Science Foundation and an anonymous benefactor interested in the project at the Station. Without the support from these two sources, we could not have begun the project of building the present 24-foot Agassiz Station radio telescope and its electronic apparatus, and we would not now be thinking hopefully of a new 60-foot reflector with much improved electronic equipment. We are depending for the remainder of our funds for basic operation on assistance received from Harvard University, and at a critical stage in the construction of our electronic apparatus, the Research Corporation came to our rescue with a special grant.

At Ohio State University, the remarkable developments in antenna design by J. D. Kraus have been supported by the University and in part by NSF. The Carnegie Institution of Washington itself is financing the three projects under way at the Department of Terrestrial Magnetism. Navy and Air Corps funds have played an important part in some of the remaining projects -- especially those relating to solar research. All of us in the field of radio astronomy have reason to be grateful for the splendid ways in which the U. S. Navy has supported Dr. Hagen's project at the Naval Research Laboratory in Washington.

Radio astronomy holds a special position as a cross-field science, part astronomy, part physics and part electronic engineering, for which technical advances in electronics and in the design of antennas are of critical importance For success in the field, the radio astronomer requires the strongest possible support from industry in the design and construction of his sensitive apparatus.

In return for the help that has been freely given by some of the leading electronic industrial concerns, especially by manufacturing companies of radar antennas , the radio astronomer performs as a part of his researches some very exhaustive tests of the equipment, and makes recommendations for improvements that may have value for applied and industrial research in the field.

Cooperation as suggested above has proved all important in the development of radio astronomy at Harvard University, where my colleague Harold I. Ewen and I have received the strongest possible support not only from our colleagues at Harvard and Massachusetts Institute of Technology, but also from New England industry. I am mentioning this simply because similar opportunities for cooperation exist in at least eight or ten other academic communities in the United States and we must take advantage of this happy circumstance in the development of radio astronomy enterprises elsewhere in the country.

Before too many years will have elapsed, the United States should have one or more new major establishments with first-rate equipment in the field of radio astronomy. Associated Universities, Incorporated -- the organization that has with such signal success initiated and operated the Brookhaven National Laboratory -- is inquiring into the establishment of a large cooperative radio observatory somewhere in the eastern United States. All of us interested in the development of radio astronomy in the United States should give the fullest support to this project.

After far too long a period of relatively little activity, radio astronomy in the United States is finally getting really under way. As a result of our first efforts, we have obtained scientific results that are recognized to be of value. Experienced personnel is beginning to accumulate and graduate training on a modest scale is under way. We are developing our instrumentation and we are beginning to think in terms of equipment that should make possible really worthwhile research advances. I am sure that if scientists and administrators continue to give it increasing support in the years to come, we shall be in a position to make vital contributions to the new science of radio astronomy.

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