OPTICAL AND RADIO ASTRONOMERS IN THE EARLY YEARS

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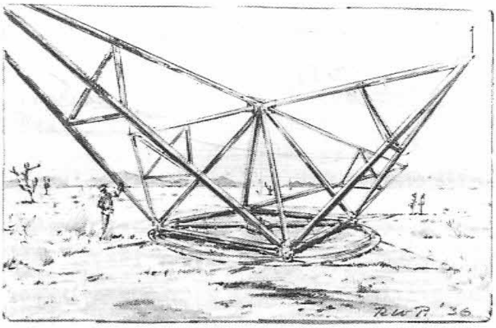
Radio noise from space was detected by Karl Jansky in 1931, working at the Bell Telephone Laboratories (Jansky 1933). This revolutionary discovery broke the barrier confining astronomical knowledge to the information contained, and the relevant physics, within the narrow band of wavelengths accessible (an octave and a half), and to positions and motions under purely gravitational forces. Jansky's wavelength was ten million times longer than that of light. His signals were radiated from the galactic center, 10,000 parsecs distant. The long wavelengths he used resulted in low angular resolution. There was no radial velocity information, no sharp spectral features (the first line was found twenty years later). For such reasons, and perhaps because he was an electrical engineer, no astronomer beat a pathway to his door; in fact I have never met any astronomer who personally knew him. Public recognition came only as an article in the New York Times (May 5, 1933) and a radio interview. His relevant bibliography includes only seven entries over the years 1932 to 1939, and he died young (see the article by Sullivan in this volume for further information on Jansky). As a summer resident of New Jersey seashore resorts in the early 1930s, I wore golf knickers, possibly even a hip flask, and drove an open car with a rumble seat (oh nostalgia!) past the giant antennas of the transatlantic radio transmitters for which Jansky's studies of noise background were to find the best operating wavelengths. Although I felt no premonitory twinges, I met my wife there, soon became interested in Jansky's results, and my life became linked with that place and time.

In 1936, G.W. Potapenko and D.F. Folland of Caltech carried a receiver into the Mojave desert, and with a simple, rotatable antenna confirmed Jansky's results. Potapenko tried to persuade R.A. Millikan to fund an antenna the size of a boxcar, on a rotating wooden frame. But the cost, $2000, proved too expensive; only a pencil drawing exists by Russell W. Porter (whose sketches of the 200-inch reflector were so effective), showing the scale and the simplicity of the design (Fig. 1).

Figure 1. A proposed Caltech radio antenna, dated 1936.



Theorists paid a little attention; the first was R.M. Langer (1936). At Harvard soon afterwards F.L. Whipple (then a young faculty member) and I (a graduate student) attempted to explain Jansky's results quantitatively and to suggest a source (Whipple & Greenstein 1937). Our explanation was thermal radiation from heated dust; we at first did not understand Jansky's engineering units and the effective collecting area of his antenna. We could have visited Jansky at Bell Telephone Laboratories but, unfortunately, we never did. At that time, dust and calcium and sodium were the only known constituents of interstellar material. The known gases could not radiate at Jansky's wavelength. We failed to account for the strength of his signal by a factor near a hundred thousand. The theoretical model for our radiative-transfer computations assumed that dust was concentrated, with the stars, to the center of our Galaxy. We found that the dust temperature might rise to 30 K, ten times hotter than near us in the Galaxy. But Jansky's low frequency data required over 100,000 K. Our attempt was typical of ideas of some astrophysicists for fifteen more years. As the radio observers found more and more intense sources, astrophysics responded with hotter thermal processes, e.g., in the ionized hydrogen gas in space, which reached 10,000 K (but was optically thin). We now realize that most radio noise from discrete sources is non-thermal in origin, a fact only apparent after critical discoveries in the early 1950s.

World War II brought physicists and engineers into the development of radar, high-frequency receivers and antennas of large aperture and high gain. American astronomers first met such people at the M.I.T. Radiation Laboratory; for instance, E.G. Bowen brought high-frequency tubes from England and others came to know R. Hanbury Brown. Many such Englishmen, like John Bolton, decided to work in Australia at the end ot the war in the Pacific. The Sun was detected in the radio by J.S. Hey and given a high security classification. The first publications in America were by Grote Reber, the ultimate scientific amateur, a radio engineer who built his own 30-foot tiltable paraboloid in his back yard. Self-taught, ingenious, with a few thousand dollars he found the galactic center at 160 Mc/s, later at 480 Mc/s. He published maps in the Astrophysical Journal (1940; 1944; also see the article by Reber in this volume). He saw features in his Galaxy map, e.g. a concentration in Cygnus. His results showed that dust obscuration was negligible at radio frequencies; he also developed an approximate free-free emission theory. His articles faced somewhat difficult refereeing at the Yerkes Observatory where O. Struve was Journal editor. Struve and G.P. Kuiper first visited Reber's laboratory; later I also did, and became involved with him, and other Yerkes theorists, interpreting the radio spectrum.

After the war, many others extended the observations of the Sun and Galaxy with improved equipment, 60-200 Mc/s (Hey 1946; Hey, Phillips & Parsons 1946; Pawsey 1946). The spectral energy distribution of sources which emerged decreased with frequency — a power law which was quite impossible to explain by a thermal source, where flux is proportional to frequency squared, if optically thick, and nearly flat, if thin. Why did we pursue a thermal explanation? Probably because most things radiated thermally, as did the surfaces of stars and planets, or fluoresced, as did gaseous nebulae. Knowledge of the major components of interstellar space was limited. Lasers and masers were not invented and few believed high-energy physics had much role in the astronomical Universe. For example, a leading cosmic-ray physicist in a lecture at Yerkes said, in the late 1940s: "The only thing cosmic about cosmic rays is their place of origin, which is unimportant." Such hindsight makes for unpleasant breast-beating, and astronomers were not alone in conservatism. Some points should be made in partial explanation:

(1) Early radio flux measurements had so poor an absolute calibration that the shape of the continuum was truly uncertain.
(2) Only post-war did we learn of the high brightness temperature of solar noise storms which had blanketed British radar.
(3) The concept of a plasma containing relativistic particles was unfamiliar; magnetic fields were required for cosmic-ray isotropy, but their existence was established only in sunspots.
(4) Primary cosmic-ray electrons were rare or non-existent as observations then stood; they could be of secondary origin.

The Yerkes group (Henyey & Keenan 1940; Greenstein, Henyey & Keenan 1946) therefore pursued further the theory of thermal free-free radiation by hot, ionized gases. Using the standard formulae, including quantum-theory factors, of D.H. Menzel and C.L. Pekeris (1935), it is possible to relate classical and quantum physics by the correspondence principle. Thus the strengths of free-free, bound-free and bound-bound hydrogenic transitions can be derived. The review by Reber and myself (1947) mentions excited fine-structure transitions of hydrogen and the high n-value recombination lines such as n = 340 near 5 meters! For us, emission lines from ionized hydrogen were implicit in thermal theory (and were indeed found much later). A thermal model worked for the baseline, quiet-sun, coronal emission (temperatures above 1,000,000 K), but failed for the strong solar bursts or any power-law energy distribution. It failed hopelessly at Reber's and Jansky's low frequencies. Had we thought deeply, we might have predicted the existence of masers through stimulated emission in dense, ionized gas (see van de Hulst's contribution in this volume). But attention was soon focussed on a new type of observation that became part of the solution. In 1949, attempting to test a stellar-atmosphere prediction that S. Chandrasekhar had made, W.A. Hiltner and J. Hall independently found optical polarization caused by interstellar dust. The only obvious explanation was that organized magnetic fields were present in the Milky Way, containing enormous total energy. E. Fermi (1949) had tried to understand the acceleration of protons to cosmic-ray energies by moving, magnetized clouds. The energy density of cosmic-ray protons proved comparable to that in the required magnetic fields. If the cosmic ray protons detected on Earth had been accompanied by high-energy electrons, a framework for understanding radio-astronomical sources would have existed using ideas in the wind before 1948. But cosmic-ray electrons are rare because they lose energy so rapidly; it is only in the non-equilibrium regions of our Galaxy (and strong radio sources) or shocked gas near exploding stars that they live their brief and glorious span. The explanation of the polarization in space by aligned dust grains (Davis & Greenstein 1951) did in fact require higher magnetic fields than were thought reasonable, matching those found only in the 1970s in dense molecular clouds. The fields in strong radio sources had to be amplified by the same types of phenomena producing the relativistic electrons. Fermi (1954) discussed some of the problems of production, leakage and decay of cosmic rays, and of the interstellar magnetic fields.

Reber and I (1947) wrote the first post-war resumé of the exciting new discoveries in radio astronomy. Writing that review of a continuously changing experimental science was an educational experience for me, as an astrophysicist. Regions of emission other than the galactic center were found numerous. Surveys had been made over a wide range of frequencies. A rapidly fluctuating signal was found from a small region in Cygnus, difficult to explain as refraction in an electron cloud (now interpreted as scintillation from a "point" source). Theories reviewed were found generally unsatisfactory, because of the high brightness temperatures of the sources. The solar phenomena then known included intense noise storms, circular polarization and possible gyromagnetic radiation from sunspots. An addendum I wrote four months later mentions flare-associated impulsive bursts, the detection of the "quiet" sun, the optical thickness of the corona at low frequencies and the desirability of a search for hyperfine emission of hydrogen. Data had far outrun interpretation, and little we reported had involved any cooperation with astronomers. The former radar wizards did their own interpretation, starting careers in England and Australia as a new breed, radiophysicists. In the United States radio telescope building began five years later at sites near, or in connection with, optical astronomers, e.g., Harvard, Michigan and Cornell. At first the natural academic links had been with electrical engineering groups such as the Naval Research Laboratory, Ohio State, and Cornell, often supported from military funds. A major impetus came from the Netherlands, where prediction of the 21 cm line by H.C. van de Hulst (1945) combined with the strong interest of J.H. Oort in galactic structure and rotation. (On my oral thesis examination in 1937, Harlow Shapley had asked me how neutral interstellar hydrogen might be detected. The importance of H I for galactic structure and star formation was obvious, but I had no ready answer, knowing only how to find ionized hydrogen.) It was natural for solar radio astronomy to have strong connections with those who studied solar and flare activity (e.g., the High Altitude Observatory). International organization started with URSI, as a meeting place for electrical engineers. Later the IAU provided a home and a Commission, and astronomical journals actively solicited radio astronomy papers.

Given the European dominance of pre-war astrophysics, it is now interesting to re-read a fascinating paper by a leading theorist, A. Unsöld (1949). While the conclusions are often wrong, Unsöld paid careful attention to what the experimenters had found and tried to explain their results, scaling from the radio phenomena found in the Sun, as an example. He introduced many of the leading concepts of the high-energy Universe in this analysis:

(1) Solar radio noise cannot be thermal; only at its lowest level is the quiet-sun flux explicable by thermal, free-free emission from the chromosphere and corona.
(2) Solar cosmic rays are produced by moving magnetic fields in surges and prominences; particles up to 10 GeV are produced, and locked onto sunspot lines of force in gyromagnetic motion.
(3) Extrapolating from the Sun to galactic cosmic-ray particles a magnetic field in space near a microgauss is required if the field is to produce the isotropy in direction of arrival.
(4) The magnetic energy density is nearly the same as that of cosmic rays, with both greater than the random kinetic energy of gas clouds, stars, or the energy density of starlight.

But even such good, pioneering astrophysics may be premature. In his attempts to account for the discrete radio sources, then known to be common but not yet identified, Unsöld invoked the existence of a class of numerous, highly active, faint M-dwarf flare stars, with very strong magnetic fields and noise storms of supersolar strength. He explained the supposed radio variability of Cygnus A, known then as a point source, as super-flares on a nearby M dwarf. He was wrong, but he had been misled by the radio astronomers; the Cyg A source was not itself variable, but twinkled like a star in the turbulent ionospheric plasma.

While Unsöld was wrong on the discrete radio sources, we are not much better off today, since we still posit many "magical" devices. Thus, interstellar magnetic fields originate from initial conditions of galaxy formation; relativistic electrons may come from supernova explosions. We require a family of phenomena in small, intense radio sources — supersonic gas motion, magnetic shocks, violent accelerations — which we hope may be indirect consequences of energy released during collapse under gravity. Very-long-baseline interferometry reveals in the heart of a quasar motions apparently faster than light; optical and near-ultraviolet spectroscopy show very hot surrounding gas and jets of invisible plasma. Displacing the origin of radio noise into a deep potential well, perhaps that near a black hole, seems plausible, but is still worth some concern. While solar cosmic rays are soft, a few hundred MeV, the electrons in intense radio sources reach a few hundred GeV, and must be continuously replaced.

The change from the old model based on scaling up the active Sun to the present mysterious central engine came about through the identification of strong extragalactic radio sources such as Virgo A (M87) and Cygnus A, the realization of their enormous distances, based on the cosmological interpretation of their redshifts, and the further identification of other faint, disturbed galaxies with large redshifts. Equally important were the identifications of two supernova remnants, Cassiopeia A and Taurus A (the Crab nebula). (As new wavelength regions opened, the latter has since been involved in other major discoveries, such as the optical, X-ray and gamma-ray pulsar.) Central to this major advance were two remarkable astronomers of the Mount Wilson and Palomar Observatories staff. Unfortunately, they published little, and their worldwide, often handwritten correspondence has not been assembled. Walter Baade was a classical astronomer, while Rudolph Minkowski had a little more training in physics. Both were superb observers, with the patience, skill and observing time on the Mount Wilson 100-inch and on Caltech's then new Palomar 200-inch needed to study the faint objects which were identified with radio sources of small angular size. They were not young (58 and 56) in the critical years 1950-51 when they responded to the suggestions of radio astronomers to search for optical counterparts to the strongest radio sources. Their two classical papers (Baade and Minkowski 1954a,b) end with the acknowledgment: "We are greatly indebted to the members of the radio astronomy groups in Sydney, Cambridge and Manchester for their generous communications of information in advance of publication." The accuracy of radio positions had gradually increased, from a degree down to one or two minutes of arc. The radio astronomers, consulting catalogs of all types of known nebulae, sometimes found positions roughly coincident with a radio source, but had no way to measure distance. A radio source roughly coincident with a bright, large galaxy usually proved to be intrinsically weak (as is our own Galaxy). The two strongest, Cas A and Cyg A, had no easily seen optical counterparts. Radio resolution and pointing accuracy were 100 times inferior to the optical results. Since both disciplines needed each other, the time was ripe. For almost two years, letters and discoveries were exchanged freely (for example, see the article by Smith in this volume). In 1949-52, Baade and Minkowski used both the 48-inch Schmidt, the new, wide-field mapping telescope, and the 200-inch to pursue investigations stimulated by radio astronomers. For us in Pasadena, this stimulation led to the eventual founding of our radio astronomy group, under John Bolton, in 1955, and to the Owens Valley Observatory, operating by 1959. This was first staffed, or visited, by many with whom Baade and Minkowski had corresponded — Bolton, G.J. Stanley, F.G. Smith, B.Y. Mills, P. Scheuer and K. Westfold.

Figure 2. (Left) Walter Baade (1893-1960)(photo: early 1950s); (right) Rudolph Minkowski(1895-1976)(photo: early 1940s).

Those who know Baade and Minkowski only as names have missed the rare experience of two extraordinary men. I am indebted to the photo-library of the Mount Wilson and Las Campanas Observatories for the two portraits from their historical collection shown in Figure 2. Walter Baade had come to Pasadena in 1931, from Hamburg. He was born in Westphalia; he was an intense person, with excellent taste in wine, humor, food and conversation. He had even better taste in astronomical puzzle-solving, aided by an enormous memory for astronomical facts. He was committed to a program of studying the distances and stellar populations of nearby galaxies, the cosmic distance scale, and the expansion of supernova shells. Yet he could always find time to browse, as in his critical 1952 discovery of the two types of Cepheids, the first major step in the great enlargement of the distance scale of the expanding Universe. Rudolph Minkowski, born in Strasbourg, came to Pasadena in 1935 as a refugee from Germany. He was a large, gentle person, also fond of astronomical puzzles, and more familiar than Baade with atomic physics and spectroscopy. He studied the physics of, and the expansion in the Crab, and the nature and spectra of supernovae. Lunches at Caltech with these two, at least weekly, made the 1950s a precious decade for many of us. These two classical astronomers had remarkable freedom in their speculations, combined with the best observing talent at a time when photography was still the dominant technology. They were always re-educating themselves. One might say that these best practitioners of a mature, well-instrumented, experimental science were ready with open minds to look at the novelties revealed by the pioneering instruments in the new, radio-wavelength region.

Taurus A, after an early radio position by Bolton(1948), had been identified with the Crab nebula, a supernova remnant, by Bolton, Stanley & Slee (1949). Smith (1951) then found a radio position good to a few minutes of arc, and Mills (1952) to a minute of arc; furthermore, the radio size and shape resembled that of the Crab nebula. This information could not have fallen into better hands, given Minkowski's study (1942) of the spectrum of the filamentary expanding cloud, and of the amorphous inner continuum whose spectrum he did not understand. Baade (1942) had also studied the expanding filaments and identified the Crab as the remnant of the supernova of A.D. 1054. Both worried about the possible stellar remnant, and noted the featureless spectrum of one of the close central pair of faint stars. Minkowski established that it was hot and dense and did not radiate like a blackbody. There were many false starts, including errors in the computation of continua of hot plasmas. When Minkowski and I (1953) undertook a full theoretical re-analysis of the spectrum, we found that no thermal source could explain the central star, or the optical and radio energy distribution of the amorphous nebular mass with its nearly flat continuum lacking photo-ionization jumps. We noted, with alarm, that the Crab emits radio waves twelve orders of magnitude stronger than the Sun. Bolton had written us that the Crab's emission dropped only slowly at high radio frequencies, which was not explained. Nor could we explain how ultraviolet radiation from the central star, no matter how hot, could maintain the luminosity of the nebula for 900 years. We estimated that the shock-heating resulting from turbulence would produce temperatures above a million degrees. I mentioned nuclear-energy sources, suggesting possible abundance anomalies produced in the explosion of the collapsed remnant of a massive star, since hydrogen was deficient relative to helium, and carbon or lithium might have been produced from the decay of radioactive beryllium. Our first mention of the synchrotron process was not until 1954 (Minkowski and Greenstein 1954) quoting "newly-arrived" papers by Shklovsky (1953a,b). While our quantitative study had produced little real progress, we felt that the origins of both radio and optical radiation were linked to an unknown, energetic process.

In a certain sense, the "new physics" required explains the failure of these early interpretations; we had not specifically invoked cosmic ray electrons. But such theories cannot have much slowed the progress of the radio observations. The radio astronomers improved their techniques. The Universe seemed full of the unknown. When an important new technology becomes available, such "accidental" discoveries are normal, and most theories prove, in retrospect, to have been conservative. An argument raged in England as to whether the majority of the unidentified sources were stars or galaxies, since faint M dwarfs and faint galaxies both are isotropically distributed, as were the radio sources. Radio observers seemed reluctant to ascribe to galaxies the powerful energy sources needed if the radio sources were distant objects. They reasoned this way since most identified galaxies were weak emitters, i.e., normal galaxies. With hindsight the theorists come off better if one reads today the (unpublished) "Proceedings of the Conference on Dynamics of Ionized Media" (April, 1951) held under the chairmanship of Professor H.S.W. Massey at University College, London. I am grateful to Tommy Gold for a copy. In a paper there, Gold has gems such as: "The most favorable conditions [for radio sources] would be expected in the neighborhood of collapsed, dense stars. Their magnetic field must be stronger than before collapse...." This suggests pulsars sixteen years before their discovery. Also: "If for example one supposes cosmic rays to be as intense in the whole Galaxy as they are here, then it would suffice if one part in a million of the power they dissipate by collisions appeared in the form of radio noise." While high-energy electrons rather than protons are needed, the suggestion is close. If one combines these two ideas -- collapsed, but massive objects, and radiative loss by high-energy electrons -- one has a good contemporary answer. What useful conclusions can we reach from such American and British struggles for understanding? Theory may often delay understanding of new phenomena observed with new technology unless theorists are quite open-minded as to what types of physical laws may need to be applied; conservatism is unsafe. Likewise, poor data often throws plausible theories off track, since theorists may trust current "discoveries" based on incorrect data. In astrophysics, historically, theories have only seldom had predictive usefulness as guides to experimenters. But as an observer, I believe that good new observations may shed a brilliant light, as was the case with the use of the improving radio data by Baade and Minkowski.

Before 1950 identification of radio sources fared poorly, in that only 7 of the 67 known sources had been identified. Why? Now, two-color photographs of the sky of the Palomar-National Geographic Society Sky Survey, using the 48-inch Schmidt, make it possible for anyone to make a first search for, and to identify radio, infrared or X-ray sources. In the early 1950s, however, this northern sky map was only beginning to become available. It had high positional accuracy, reached beyond 19th magnitude, had resolution of 1 or 2 arcseconds, and finally covered the northern two-thirds of the sky. Minkowski was charged with the inspection and acceptance of plates as taken, as well as preparing the copies for distribution, but no copies yet existed. In addition, Baade and Minkowski had a large share of the dark-sky observing with the new 200-inch telescope and could exploit its enormous power and fast focal ratio. The work on the two classical papers on radio sources by Baade and Minkowski (1954a,b) was initiated in 1952. They first show in beautiful photographs the peculiar structure of extragalactic sources and the unusual emission-line spectra, observed with a high-resolution, faint-object spectrograph designed by I.S. Bowen. The supernova remnants had extraordinary filamentary structure, in giant bubbles of gas, with hypersonic velocity differences between filaments (Cas A). Some of the extragalactic radio sources had unusual structure on the best photographs, e.g., Cyg A, Vir A = M87, Per A = NGC 1275, Cen A = NGC 5128. They also had strong emission lines, a fact which later proved a common and useful feature for identifications and velocities of radio galaxies. Cyg A was interpreted as two galaxies in collision. M87 had a one-sided polarized jet (Baade 1956a). NGC 1275 had strong emission, as did the Seyfert galaxies, but was apparently undergoing collision, because two systems of velocities co-existed. Further, independent of distance, Cyg A radiated more energy over the radio frequencies than in the optical region, a truly remarkable fact. The collision hypothesis was an unfortunate trap for them (and myself), since it apparently provided sufficient energy from gas-cloud collisions at high relative velocity. Many intrinsically weak radio sources proved to be nearby "normal" galaxies, with eight listed for which Cambridge or Manchester positions lay near apparently large galaxies. Thinking about identifying sources as stars, they say: "A slim chance may exist of obtaining positions of required accuracy from occultations of sources by the moon" — the method later used by C. Hazard, M.B. Mackey and A.J. Shimmins (1963) to locate 3C 273 accurately, permitting the first identification of a quasar with high redshift by M. Schmidt (1963). The most striking single result by Baade and Minkowski was that one of the most intense radio sources, Cyg A, was an 18th magnitude galaxy at a redshift of z = 0.056, or 16,830 km/s. With their value of the Hubble constant this implied a distance of about 30 million parsecs (now revised to 250 Mpc). Its luminosity was extremely high, and was concentrated in the radio frequencies. Strong radio galaxies were indeeed different!

Soon afterwards, other classical astronomers solved the very non-classical problem of the Crab nebula and its synchrotron continuum (Oort and Walraven 1956). Magnetic fields and high-energy electrons to 100 GeV, constantly renewed, were needed. Baade's (1956b) observations of the continuum through polaroid showed nearly complete polarization. He had already established the variability of hazy features near the central star. The high-energy Universe was being forced on us by nature.

The beginning of the high-resolution radio maps came soon. R.C. Jennison and M.K. Das Gupta (1953) used an interferometer to image Cyg A in detail, and found it was double-lobed, with radio emission outside the optical galaxy. By 1960 when interferometers revealed the double-lobed structure to be common, simple positional coincidence no longer proved identification. Soon, on the theoretical side, the upwards revision of the distance scale meant that the volumes of the magnetized plasma were so large that constraints on the total energy were serious -- both in magnetic fields and relativistic electrons. Real doubts arose whether even nuclear energy could suffice, so that the invention of a radical new driving engine became a necessity.

As a result of such excellent early cooperation, observations by radio astronomy techniques clearly became essential, and especially so for cosmology. The pressure for one's own radio observatory was irresistible by 1952, when Baade, Minkowski and I began to press strongly for Caltech's entrance into the field. We were fortunate in our leadership, since President Lee A. DuBridge had run the wartime M.I.T. Radiation Laboratory, and my Division Chairman, R.F. Bacher, was familiar both with high-energy physics and our goals in optical astronomy at Palomar. Evidence accumulated that the radio sky was at least as informative as the optical. The new window contained emission and absorption lines. The high-energy Universe had led to a theoretical explanation, the synchrotron process, and an enigma, the energy source. A first major attempt to review the field and to produce a synthesis of knowledge occurred during a conference held in Washington, D.C. in January, 1954, sponsored by the National Science Foundation, the Carnegie Institution of Washington, and Caltech; I acted as chairman for the organizing committee. Abstracts published (Greenstein 1954) came from Australia, Manchester, Cambridge, the Netherlands, the Naval Research Laboratory, Ohio State, Canada, Cornell, Michigan and the High Altitude Observatory. Antenna-design topics included the long fought-over question of "big dish versus interferometer array". New lines, other than hydrogen, were predicted by C.H. Townes in a prescient paper. B.J. Bok discussed results on galactic structure using the 21-cm line. One practical effect was pressure for a cooperative radio observatory, which with NSF support, eventually became the National Radio Astronomy Observatory. There was clear realization that radio astronomy had an indefinitely long and happy future, and was deserving of broad support by physicists and astronomers. The "early years" had come to an end.

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