



David S. Heeschen

1926–2012

BIOGRAPHICAL

*Memoirs*

*A Biographical Memoir by  
K. I. Kellermann*

©2014 National Academy of Sciences.  
Any opinions expressed in this memoir are  
those of the author and do not  
necessarily reflect the views of the  
National Academy of Sciences.



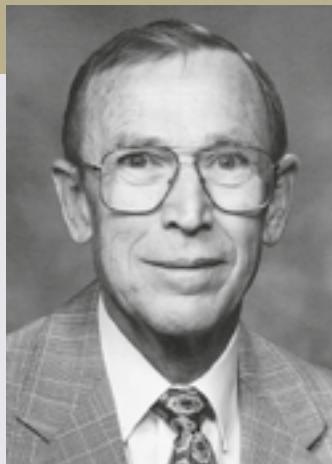
NATIONAL ACADEMY OF SCIENCES

# DAVID SUTPHIN HEESCHEN

March 12, 1926–April 13, 2012

Elected to the NAS, 1971

David S. Heeschen was one of the first radio astronomers to be trained in the United States. Starting at Harvard, and later at the National Radio Astronomy Observatory (NRAO), his pioneering research ranged from the distribution of galactic hydrogen to the study of the distant radio galaxies and quasars. As the long-serving Director of NRAO, Heeschen guided the institution from a tenuous start to recognition as the world's preeminent radio observatory. During his 18-year leadership beginning in 1961, the 140-foot and 300-foot NRAO radio telescopes and the 4-element radio interferometer were completed in Green Bank, West Virginia; the 36-foot telescope was built in Tucson, Arizona; and the Very Large Array in New Mexico became the premier instrument in radio astronomy. Over this same period, Dave carefully guided the transformation of radio astronomy from a hands-on approach where a few individuals designed, built, and used their instruments, to modern, user-oriented facilities with large support teams and visiting observers.



A handwritten signature in dark ink that reads "Dave Heeschen". The signature is written in a cursive style.

By K. I. Kellermann

## The early years

David Sutphin Heeschen was born in Davenport, Iowa on March 12, 1926 and grew up in the Chicago area. He was the only child of Richard George Heeschen, a chemist, and Emily Richmond Sutphin. Like so many others of his generation, Dave's family endured many hardships during the Depression. At an early age Dave learned to ice skate, first on the frozen Mississippi River near Davenport, and later on the Chicago canals, and he continued to enjoy the sport with his children. He was fascinated by boats, and in school he was motivated by a burning desire to attend the Naval Academy and become a naval officer, a goal quickly repressed by a one year stint in the Army near the end of World War II. After being discharged from the Army in 1945, Dave followed his father to enroll at the University of Illinois, where he intended to study agriculture. Instead, he became more interested in math and science. He received his BS degree in Engineering Physics in 1949 and his MS in Astronomy in 1951 from Illinois, and then

went on to study astronomy under Bart Bok at Harvard University. Although he completed his PhD dissertation in 1954, he had not yet passed Harvard's language requirement, so his degree was delayed until 1955.

Dave Heesch and Ed Lilley were the senior students among the cadre of Harvard astronomy graduate students working on radio astronomy projects. This included T. K. Menon, from India, May Kaftan-Kassim from Iraq, William E. Howard III, Frank Drake, Campbell Wade, and Nannielou Hepburn Dieter, all of whom went on to distinguished careers in radio astronomy, and many of whom later formed the core of the National Radio Astronomy Observatory's early scientific staff. Dave worked together with Lilley on developing the Harvard radio astronomy project from its very beginning in 1953, and then took a leading role in putting the department's 24-foot and later 60-foot radio telescopes into operation.

After completing his PhD dissertation, Dave left Harvard for what he thought was an assistant professor position at Wesleyan University in Middletown, Connecticut. However, because he had not yet received his degree as a result of failing his German language exam, Wesleyan reduced his appointment to instructor and cut his salary about 50% from what had been agreed to. According to his son Richard, "Fifty years later this still annoyed him," and for many years Dave gave 1954 as the year of his PhD degree. While still at Wesleyan, Dave continued to maintain his connections with the Harvard radio astronomy program. He returned to Harvard in 1955 as a lecturer and research associate. He continued his research on atomic hydrogen gas in the Galaxy and was in charge of planning the new 60-foot radio telescope, which went into operation in the spring of 1956.

Dave met Eloise St. Clair at a University of Illinois bridge club. They were married in 1950, and had three children, Lisa Clair, David William, and Richard Mark.



Dave Heesch at the Danville Racetrack in his Austin-Healy.

## A new era in radio astronomy

Although the first investigations in radio astronomy were made in the 1930s and 1940s in the United States by Karl Jansky at Bell Labs, and then by Grote Reber working from his home in Wheaton, Illinois, by the early 1950s the United States had clearly fallen behind in this rapidly developing new field. Not only were exciting new scientific discoveries being made in the U.K., the Netherlands, and Australia but in several countries radio astronomers were already developing ambitious plans for large new radio telescopes. Aside from the astronomical opportunities, it was clear during these tenuous Cold War days that the development of antennas and instrumentation for radio astronomy could also contribute to military readiness and to civilian communications as well as to the important image of national prestige. Although the military was funding a few modest university programs as well as some in-house programs at the Naval Research Laboratory (NRL) and the Air Force Office of Scientific Research, it was clear that a more ambitious program would be needed if the United States were to establish leadership in this emerging new field.

By 1956, Bart Bok, Donald Menzel, and other Harvard faculty had been instrumental in convincing the new National Science Foundation (NSF) to fund a national facility for radio astronomy that would build and operate instruments that were deemed too large and too expensive for a single university. They, along with other east coast science power brokers including Julius Stratton from MIT, I. I. Rabi from Columbia, and John Hagan at NRL convinced the NSF to award the contract to manage the new National Radio Astronomy Observatory (NRAO) to Associated Universities Inc. (AUI). Since 1946, AUI had managed the operation of the very successful Brookhaven National Laboratories, but was awarded the NRAO contract only after overcoming strong opposition from critics such as Merle Tuve at the Carnegie Institution's Department of Terrestrial Magnetism, who argued that NSF money should go to "active research astronomers, not to physicists, engineers, or administrators."

Harvard was one of the then nine university members of AUI along with MIT, Cornell, Johns Hopkins, Columbia, Yale, the University of Pennsylvania, Princeton, and the University of Rochester. While still working at Harvard, and encouraged by Bart Bok, Dave participated in the search to find a suitable site for the planned new radio observatory that would be free from man-made radio interference. In January 1956 Dave became a consultant to AUI, and resigned his Harvard position to accept a two-year full time appointment to join AUI in the office of the President, Lloyd Berkner, starting on July 1, four months before the NSF agreed to award the contract to AUI. Dave became

the first member of the NRAO scientific staff, and a year later he moved with his family from Harvard to the remote town of Green Bank, West Virginia, where the new radio observatory would be located.

It was difficult to find a qualified person to become NRAO director. Bart Bok, Leo Goldberg, Jesse Greenstein and other astronomy leaders all declined offers on the grounds that they didn't know enough radio astronomy, or enough electronics, or that the observatory was too remote, or that the administrative responsibilities would not allow sufficient time for research. Finally, Otto Struve, a distinguished astronomer from the University of California and member of the NRAO Director Search Committee agreed to take the job, and Dave became assistant to the director and chairman of the Astronomy Department, with continuing responsibilities for the scientific staff and general oversight of the observatory's scientific operations.

The following years were challenging ones for Heeschen and for NRAO. The construction of the first major NRAO telescope, the planned 140-foot equatorially mounted dish, proved to be more than Struve and AUI could handle; NRAO had no competitive radio telescopes, and there was very little interest from outside scientists to use the modest NRAO facilities. Meanwhile new powerful radio telescopes had been developed at Caltech and elsewhere with funding from ONR. The 140-foot antenna was years behind schedule and way over budget. The contractor was fired, and NRAO was threatened with closure. AUI president Lloyd Berkner, who had been the driving force in establishing NRAO, and the NRAO director, Otto Struve, each resigned, and Dave Heeschen was appointed acting director. Joe Pawsey, a distinguished Australian radio astronomer, agreed to take the job as NRAO director, but was struck ill with a brain tumor and died before he could assume the position. Somewhat in desperation, in 1962, AUI appointed Dave as director of NRAO. He was only 36 years old, and faced what appeared to be the impossible task of fulfilling the ambitions of those who had fought so hard for the establishment of a national radio observatory whose future now appeared uncertain.

### **Open skies**

One of Dave's first moves was to restructure the management of the 140-foot telescope project by assigning control to the NRAO staff in Green Bank rather than to the New York-based AUI staff. He appointed a project manager from Brookhaven, who successfully oversaw the completion of the telescope which was finally dedicated in October 1965. The 140-foot telescope was an instant success, with the detection of the long-

sought radio recombination lines from high energy level transitions of simple atoms, an achievement followed by a series of discoveries of various interstellar molecules.

Even before the completion of the 140-foot telescope, Heeschchen initiated the construction of a precision 36-foot radio telescope for observations at short millimeter wavelengths. Although there were again serious problems with the contractor, the NRAO 140-foot and 36-foot radio telescopes, operating at centimeter and millimeter wavelengths respectively, soon became the most sought after radio astronomy facilities in the world. Between them, they led to

the discovery and then study of numerous molecular species in the interstellar medium, and the competition to be the first to discover a new molecule was intense. At the same time, there was also great pressure to use the telescopes to study other phenomena, such as the radio emission from radio galaxies, quasars, cosmic OH and H<sub>2</sub>O masers, and the newly discovered pulsars. The demand for telescope time far outweighed the available time. It was hard to distinguish among the different proposers as they all proposed to use the same antenna and the same NRAO instrumentation. In order to fairly assign telescope time, Dave initiated a system of outside reviewers to advise on the scientific merit and feasibility of each proposal, a practice that has been widely duplicated and is now common throughout the global astronomical community. He also started what was probably the first “users committee” to provide feedback to the director on priorities for new instrumentation and on observatory operations, a now common practice among both public and private astronomical facilities.

It was difficult to recruit staff to live and work in the isolated West Virginia environment. Probably the most contentious decision Dave made was the recommendation to move the NRAO headquarters to Charlottesville, Virginia, which was an attractive university town to live in, but still close enough to Green Bank to maintain easy travel between the headquarters and the observatory. The proposed move was strongly opposed by I. I. Rabi,



T. K. Menon, Dave Heeschchen, Russell Anderson, and Bart Bok at the Harvard 60-foot radio telescope, 1956.



Dave Heeschen speaking at the 140-foot radio telescope dedication.

then the AUI president, who wanted the headquarters to be located at Princeton or some other major research university. Heeschen and Rabi locked horns on this, and apparently they didn't speak to each other for years after the AUI Board approved Heeschen's recommendation to go to Charlottesville.

In spite of the major discoveries in radio astronomy in the 1960s, radio telescopes traditionally had limited angular resolution, due to diffraction at the long radio wavelengths. Even the largest dishes working at the shortest wavelengths, have a resolution only of the order of a minute

of arc — comparable to that the unaided human eye. To an extent, radio astronomers were able to improve their resolution by using widely spaced antennas as interferometers, but these efforts were mostly limited to crude interpretations based on simple model fitting to the limited interferometer data. What was needed was a truly image-forming instrument that would give pictures with resolutions comparable to that of the best optical telescopes on a good mountain site.

Dave set as a goal for the NRAO to build such an instrument, calling it, for the lack of a better term, the "Very Large Array" or "VLA." There were many engineering problems to overcome, and indeed there were claims that turbulence in the Earth's troposphere would prevent high resolution radio imaging, in the same way that "seeing" limited optical telescopes to resolutions of the order of a second of arc. Heeschen personally led the design and optimization effort and the ensuing struggle to sell the concept to a skeptical astronomical community — including some members of his own scientific staff at NRAO.

A series of NSF review committees said nice words about the VLA, but gave priority to upgrading the 1000-foot Arecibo radio telescope and construction of a more modest array being proposed by Caltech. Then, as the chair of the radio astronomy panel for the 1970 NRC decade review of astronomy, Dave was able to persuade his fellow panel members that the NRAO VLA should be the highest priority for the next radio telescope project in the U.S. He then won over the even more skeptical survey committee



members, each of whom had their own priorities. Once the project was funded, Dave personally provided broad oversight to the construction of the 27-element VLA, spending every third week at its New Mexico site and taking responsibility for a number of critical but controversial design decisions. The VLA was dedicated in 1980, and has been arguably the most productive ground-based radio telescope ever built.<sup>1</sup>

The growing demands from the NSF for paper work and reporting finally led Dave to resign in 1978 after 16 years as director of the NRAO. Following a one-year leave of absence, which he spent at the Max Planck Institute für Radio Astronomie in Germany, Dave returned to NRAO, where he continued as a member of the scientific staff. Although he was looking forward to continuing his research activities that he had largely abandoned during his 18-year tenure as NRAO acting director and then director, he repeatedly responded to the call to contribute his widely respected administrative talents. In 1984 he agreed to serve as acting assistant director for Tucson operations, and in 1988 to act as assistant director for New Mexico operations.

Then, in 1989, following the collapse of the NRAO 300-foot transit telescope, NRAO quickly obtained funds to build a new fully steerable radio telescope. Atypically, the funding preceded the design or project planning. Dave agreed to be the project manager, and insisted that the new radio telescope had to be significantly innovative and not just an incremental improvement over existing facilities in other countries. He resolved to include two challenging design features: a computer-controlled adjustable surface that would compensate for deformations of the reflector due to changing wind, temperature, and the effect of gravity as the pointing of the telescope was varied; and adoption of a feed and sub-reflector system that did not block the main reflector, thus increasing the antenna efficiency and, more importantly, reducing the diffraction side-lobe response which is characteristic of conventional large parabolic reflectors.

A new project manager was finally appointed to oversee the challenging but successful completion of the 100m Green Bank Telescope (GBT) for which Heeschen had defined the exacting specifications. Since it began operation in 2000, the GBT has become, by far, the most powerful instrument of its kind in the world, with new discoveries ranging from the detection of CO in high redshift galaxies, to imaging the distribution of hydrogen in our Milky Way Galaxy, to precision timing of pulsars with a goal of detecting the effect of gravitational radiation on the arrival time of their pulses.



## An interrupted scientific career

While at Harvard, Heesch, as well as the rest of the radio astronomy group, focused their research on the 21-cm radio emission from neutral hydrogen that had been detected in 1951 by Harold (Doc) Ewen as part of his Harvard Ph.D. dissertation. Dave's PhD topic, "An Investigation of the 21-cm Line of Neutral Hydrogen in the Section of the Galactic Center," showed for the first time absorption from hydrogen gas in front of the center of the galaxy. These were challenging investigations made with what would now be described as primitive instrumentation, and had to compete with similar work being done with larger antennas at the Naval Research Laboratory and in the Netherlands, but they set the stage for understanding the distribution of atomic hydrogen in the Milky Way galaxy as well as in other galaxies, subsequently leading to recognition of dark matter in the halos of galaxies and the existence of large scale structures in the Universe.

After arriving at NRAO, Dave turned his attention to the problems of radio galaxies and later to the newly discovered quasars. Through a careful series of measurements, he made the first accurate determination of radio galaxy spectra, which provided the basis for the calibration of radio astronomy flux density scales. He was the first to recognize the important relation between the luminosity and spectra of radio galaxies, a relation still used today to discover distant powerful radio galaxies.

Following his tenure as NRAO director, Dave was able to devote more time to continue his research on extragalactic radio sources, and he discovered the intra-day variability of compact radio sources which he called "flicker." This phenomenon is now recognized as the result of scintillation due to turbulence in the interstellar medium (equivalent to the twinkling of stars), and not to intrinsic variability, so it is now extensively used to study the small scale structure in the interstellar medium.

While dealing with the administrative challenges as NRAO director, Dave did not have much time for his own research, but delighted in the scientific productivity of the NRAO facilities, and took special pride in the achievements of his scientific staff. When this author arrived at NRAO in 1965 as a young assistant scientist, Dave characteristically handed over all of his unpublished data, telling me to freely use it as needed for my own work on the same subject. He did find time, however, to use the 3-element NRAO interferometer and later the VLA to investigate the radio emission from elliptical galaxies. He discovered two galaxies, NGC 1052 and NGC 4278, each of which contained an intense small diameter radio source in their centers which are now recognized as the low

luminosity end of the broad class of active galactic nuclei (AGN) which includes the more powerful quasars.

### **Other professional activities and honors**

Dave Heesch was elected to NAS membership in 1971 and was active in COSEPUP, the NRC Committee on International Relations, as well as other NRC committees including the 1970, 1980, and 1990 decade reviews of astronomy. He was also active with advisory committees to numerous national, international, and private organizations. He held an appointment as research professor of astronomy at the University of Virginia, and received honorary Sc.D. degrees at the University of West Virginia and the New Mexico Institute of Mining and Technology. He was associate editor of the *Astronomical Journal* from 1969 to 1971, chair of the U.S. National Committee for the International Astronomical Union (IAU), served as president of the IAU Commission on Radio Astronomy and then as vice president of the IAU from 1976 to 1981. He was president of the American Astronomical Society from 1980 to 1982, and was a Fellow of the American Academy of Arts and Sciences and a Member of the American Philosophical Society. In 1980, Dave received the NSF Distinguished Public Service award, and in 1985 he received the Alexander von Humboldt Distinguished Senior Scientist Award.

### **Beyond astronomy**

Dave pursued his hobbies with the same enthusiasm and intensity that characterized his professional activities. At different stages of his life he was an avid skater, hiker, hunter, sports car driver, sailor, and ham radio enthusiast. At various times he owned an Austin-Healey Sprite rumored to have been driven by Sterling Moss, a Jaguar, a Corvette, and an MG. Aside from participating in organized events at local racetracks, Dave took pleasure in competing with other NRAO scientists in time trials on the 112 mile mountainous route between the NRAO offices in Charlottesville, Virginia and the Observatory in Green Bank, West Virginia.

Under some pressure from Eloise, Dave began to look for something that was equally exciting but less dangerous than racing sport cars, and he rediscovered his childhood fascination with boats. He bought a small one-person fiberglass sailboat, joined a yacht club in Deltaville, Virginia, on the Chesapeake Bay, and frequently competed in club races. He became part owner in a somewhat larger boat, and turned into an avid reader of sailing literature. He was fascinated hearing about adventures of ocean sailing, such as single-handed round-the-world trips. Eventually, Dave decided that he needed an ocean-going boat. Together with a prominent boat builder, Dave designed and built a 32-foot

steel hull, gaff-rigged schooner that he named *Delight*. Dave designed the boat with no motor and no electricity. The running lights used kerosene, and the toilet was a bucket attached to the mast. On its maiden voyage to Bermuda, Dave learned how difficult it is to sail into a demanding harbor, and he conceded that he might need to install an engine.

Dave was able to combine his love for sailing with his love for astronomy by writing a series of articles called “Star-gazing with Binoculars” for *Yachting* magazine. In 1976, he took a four-month

leave from NRAO to sail with his family through the West Indies. Following his retirement from NRAO in 1991, Dave and Eloise moved to Marathon in the Florida Keys, where they could enjoy nearly unlimited opportunities for sailing.

In order to keep in contact during his sailing trips, especially during ocean going trips, Dave and Eloise obtained their amateur radio licenses, AB4IE and N4TAV respectively. Characteristically, Dave didn’t stop there, but proceeded to pass the exams for the highest class of license, and became an avid hunter of contacting new countries. He took particular pride in developing his high-speed Morse code skills to contact other amateur stations in more than a hundred countries around the world, asserting that voice operation was not appropriate for the serious radio amateur.

Following Eloise’s death in 2002 Dave continued to live in Marathon, where he became more involved in community affairs. He was active in the Crane Point Hammock nature preserve, where he ran tours and served on the board of directors. He purchased an optical telescope, which he used to teach children and seniors about astronomy. But failing health and the remoteness from his family brought him back to Charlottesville. There he was able to re-engage with family and friends until his death on April 13, 2012.

### **A legacy to radio astronomy**

Dave Heeschen had a strong view of NRAO’s mission to build and operate only state-of-the-art facilities that were too large or too expensive for an individual university to



Dave Heeschen aboard *Delight*.

operate. Under his leadership, NRAO grew from a troubled organization on the verge of closure to what is widely regarded as the outstanding radio astronomy facility in the world, not only for its advanced instrumentation, but also for setting new standards for their operation. Traditionally telescope observing time had been largely confined to the resident staff of each facility, with perhaps a visitor now and then whose research did not encroach on that of staff members. Even though the NRAO and the 140-foot had been conceived with the express purpose of giving American scientists the opportunity to compete with the exciting discoveries being made abroad in this new field and the proliferation of new expensive radio telescopes, particularly in Europe and Australia, Heesch opened the NRAO facilities to all qualified users, based only on the quality of their proposed observing program, and independent of their institutional or even national affiliation. Everyone, including NRAO staff had to compete for observing time. Only in this way, he argued, would the best science be done at NRAO.

This “open-skies” policy, as it became known, has been applied to all NRAO instruments and was later adopted, at least in part, by other radio observatories, and ultimately by many optical observatories as well. Eventually, it became a policy of the National Science Foundation that open access be a requirement in return for federal funding of both radio and optical observatories. Dave Heesch is widely regarded as the father of “open-skies,” which has greatly contributed to the growth of international cooperation in radio astronomy and indeed, to the broadly changing culture of astronomical research.

Dave felt strongly that NRAO should only operate facilities that were at the cutting edge and would provide unique research opportunities. As soon as the first VLA antennas became operational, he closed down the 4-element Green Bank interferometer, which was still doing good science. He wanted his staff to concentrate on making the VLA operational. Probably more than any other single individual, Dave was responsible for changing the culture of radio astronomy from a hands-on approach by black belt experimenters to the modern user-oriented practice, and the conversion of radio astronomy to a big science designed to serve a broad user community. But he was always cognizant of the need to maintain strong programs at the universities where many of the instrumental innovations were developed, and where future NRAO staff and users are trained.

Although an imposing personality as NRAO director, Dave was very modest about his own accomplishments, and was quick to give credit to others. At the same time, he would ask penetrating questions and had no patience for weak arguments. He encouraged discussion and debate and would listen to dissenting views, but when he

made a decision, it was understood that there would be no more discussion. At one users committee meeting that he chaired, he got impatient with a distinguished committee member, and finally stood up, stating “If you don’t like it, you can find a new director.” He then left the room, leaving the committee members speechless and embarrassed.

In spite of his extensive administrative responsibilities, Dave took a personal interest in the professional growth of his scientific staff, all of whom reported directly to him, rather than to a subordinate. He remarked once that the most difficult part of his job as director was tenure decisions. He was especially supportive to the younger members of the scientific staff and took pride in their accomplishments. I recall once, for what I thought were sound reasons, I was strongly opposed to a project he had planned to modify the 140-foot telescope. Dave called a meeting of the senior staff at NRAO’s Charlottesville headquarters to discuss the project, and I drove the 112 miles over the mountains from Green Bank to Charlottesville to make my case. Dave went around the room — everyone had a chance to state their view. I think I was the only one who disagreed with him. At the end, Dave announced, “We are going to do it.” I was very disappointed and I sulked out of the room to return home. Dave saw my displeasure, came over and put his hand on my shoulder, and asked me to take charge of the project.

On another occasion, when I asked Dave for a two year leave of absence from NRAO to accept a temporary position at the Max Planck Institute für Radioastronomie in Germany, he explained that AUI rules only allowed for leaves up to one year, but if I wanted to stay for a second year, he would request permission from the AUI Board. He then added that I should understand that if I were given a second year’s leave, I was obligated to return. I responded that it was understood, but then with a twinkle in his eye, he added, “But of course you understand that we have no way to enforce that.”

Dave had no tolerance for bureaucracy, especially at the NSF. He tried to make it easy for the NRAO staff to get their work done with a minimum of rules and regulations. He expressed his management philosophy as, “Hire good people. Leave them alone. And have fun!” He abhorred long speeches, but recognizing that as the NRAO director it was his responsibility at an official observatory function to begin the expected after-dinner formalities, he would bang on a water glass with his spoon, ceremoniously stand up, clear his throat, and announce, “The bar is open.” Then he would sit down and let the guests enjoy an evening of informal discussion free of boring speeches.

## **ACKNOWLEDGEMENTS**

I am indebted to Dave's children, Lisa, David, and Richard, for providing information on his early life and some of the photographs used in this memoir. NRAO archivist Ellen Bouton was a great help in locating materials about his career at NRAO and at Harvard. Several colleagues and friends of Dave Heeschen have read an early draft of this memoir and have provided valuable input.

## REFERENCES

1. Wallace and Karen Tucker, in their 1986 book *The Cosmic Inquirers* (Cambridge: Harvard University Press, pp 7-42) describe the nearly 20 year process Heeschén guided leading to the successful construction of the VLA. See also [Trimble, V](#) and Zaich, P. Productivity and Impact of Radio Telescopes. *Publications of the Astronomical Society of the Pacific*. 118 (2006):933-938.



## SELECTED BIBLIOGRAPHY

- 1951 An Analysis of the Milky way in Perseus. *Astrophysical Journal* 114:132-140.
- 1954 With A. E. Lilley. Interstellar Hydrogen and the Local System. *Proceedings of the National Academy of Sciences U.S.A.* 40:1095-196.
- 1955 Some Features of Interstellar Hydrogen in the Section of the Galactic Center. *Astrophysical Journal* 121:569-584.
- 1960 A Color-Absolute Magnitude Diagram for Extragalactic Radio Sources. *Publications of the Astronomical Society of the Pacific* 72:368-376.
- 1961 Observations of Radio Sources at Four Frequencies. *Astrophysical Journal* 133:322-334.  
 With B. L. Meredith. Secular Variation of the Flux Density of the Radio Source Cassiopeia A. *Nature* 190:705-706.
- 1964 With C. M. Wade. A Radio Survey of Galaxies. *Astronomical Journal* 69:277:87.
- 1966 With I. I. K. Pauliny-Toth and C. M. Wade. Positions and Flux Densities of Radio Sources. *Astrophysical Journal Supplement* 13:65-123.  
 The Absolute Radio Luminosity and Surface Brightness of Extragalactic Radio Sources. *Astrophysical Journal* 146:517-522.
- 1967 Radio Astronomy: A Large Antenna Array. *Science* 158:75-78.
- 1968 Radio Properties of the Elliptical Galaxies NGC 1052 and NGC 4278. *Astrophysical Journal* 151:L135-138.
- 1970 Radio Observations of E and SO Galaxies. *Astronomical Journal* 75:523-528.  
 The Radio Spectra and Brightness Distributions of E and S0 Galaxies. *Astrophysical Letters* 6:49-53.
- 1975 With E. K. Conklin. Millimeter-Wave Observations of Elliptical Galaxies. *Astrophysical Journal* 196:347-34.
- 1981 The Very Large Array. In *Telescopes for the 1980s*. Eds. G. R. Burbidge and A. Hewitt, pp. 1-61, Palo Alto: Annual Reviews Inc.

- 1983 With J. J. Puschell. Millimeter-Wavelength Outbursts in the Elliptical Galaxy NGC 1052. *Astrophysical Journal* 267:L11-L14.
- 1984 Flickering of Extragalactic Radio Sources. *Astronomical Journal* 89:1111-1123.
- 1985 With J. H. Simonetti and J. M. Cordes. Flicker of Extragalactic Radio Sources at two Frequencies. *Astrophysical Journal* 296:46-59.
- 1987 With B. J. Rickett. The Galactic Latitude Dependence of Centimeter-Wavelength Flicker. *Astronomical Journal* 93:589-591.
- With T. Krichbaum, C. J. Schalinski, and A. Witzel. Rapid Variability of Extragalactic Radio sources. *Astronomical Journal* 94:1493-1507.
- 1988 With J. M. Wrobel. Current Star Formation as the Origin of Kiloparsec-Scale Radio Sources in nearby E/S0 Galaxies. *Astrophysical Journal* 335:677-687.
- 1991 Reminiscences of the early days of the VLA. In *Radio interferometry: Theory, Techniques, and Applications; Proceedings of the 131st IAU Colloquium, ASP Conference Series*. Eds. T. J. Corwell and R. A. Perley. 19:150-159.
- With J. M. Wrobel. Radio-Continuum Sources in Nearby and Bright E/S0 Galaxies - Active Nuclei versus Star Formation. *Astronomical Journal* 101:148-169.

---

Published since 1877, *Biographical Memoirs* are brief biographies of deceased National Academy of Sciences members, written by those who knew them or their work. These biographies provide personal and scholarly views of America's most distinguished researchers and a biographical history of U.S. science. *Biographical Memoirs* are freely available online at [www.nasonline.org/memoirs](http://www.nasonline.org/memoirs).