RADIOASTRONOMY IN THE 1990s

The decade will see major improvements in existing radiotelescopes, such as the Very Large Array, and the construction of new instruments for astronomy at millimeter and submillimeter wavelengths.

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In the years immediately following World War II, radioastronomers concentrated on following up on the accidental wartime discovery by British and American radar operators of radio bursts from the Sun. However, the continued push toward shorter and shorter radio wavelengths, combined with greatly increased sensitivity and angular resolution, quickly led to a series of remarkable and unexpected discoveries. Radio galaxies, quasars, pulsars, interstellar masers, gravitational lenses and the microwave background radiation—all now familiar topics of the astronomical and popular literature—were discovered serendipitously because of their radio emissions. A new generation of radiotelescopes to be built in the 1990s, together with major improvements in existing instruments, will give even further large gains in sensitivity, angular resolution and image quality, especially in the newly opened millimeter and submillimeter regions of the electromagnetic spectrum.

Wide variety of radio sources

Astronomers observe radio emission from a wide range of objects and astrophysical processes. Sources of nonthermal continuum emission range from ultrarelativistic plasmas that emit through synchrotron processes to stars and interstellar molecular clouds that emit through complex coherent radiation mechanisms. Sources of thermal continuum emission range from ionized interstellar and intergalactic gas that emits through a variety of processes, including bremstrahlung, to planetary surfaces that emit blackbody radiation. In addition, narrow-band spectral line emissions are received from atoms, molecules and ions in the interstellar medium, from distant galaxies and quasars and from planetary atmospheres and comets.

Following the discovery of radio galaxies in the early 1950s, astrophysicists realized that these objects require an enormous source of energy. This posed a problem that was only exacerbated by the discovery of even more powerful but extraordinarily small quasars. The recent high-resolution radio images of radio galaxies and quasars, as well as of the center of our own Galaxy, show remarkable patterns of jets, filaments and hot spots that challenge theoretical interpretation. Longstanding prob-

Millimeter Array. This artist's conception shows the 40 transportable antennas, each 8 meters in diameter, in a 250-m configuration. In the largest configuration, 3 km across, the resolution will be about 0.1 arcsecond at 1-millimeter wavelength. In the most compact arrangement, 70 m across, the MMA will have a resolution comparable to that of a single 70-m antenna, and a collecting area equal to that of a single 50-m antenna.

lems remain concerning the source of energy and how the energy is converted into relativistic plasma. Milliarcsecond-resolution observations made with very-long-baseline interferometers show that the relativistic plasma is accelerated and focused into narrow jets within a central engine only a few light-years in extent. The jets flow with apparent superluminal velocity toward extended radio lobes hundreds of thousands of light-years away.

Although radio galaxies and quasars are such powerful radio sources that they can be observed at very great distances, their anticipated application to cosmological problems has been limited because of uncertainties in how the intrinsic properties of luminosity and size evolve with cosmic epoch. By contrast, the unexpected detection in 1965 of the cosmic microwave background radiation was probably the most important discovery in cosmology in modern times. The remarkable smoothness of the microwave background provides one of the most stringent constraints on models of the early universe, and if currently planned experiments do not show anisotropies of more than a few parts in a million, then our basic understanding of the early universe may need to be fundamentally revised.

One of the most remarkable developments in cosmology in the past decade is the discovery of clusters and voids on scales of a hundred million light-years. Radio observations of the redshifted 21-cm hydrogen line from thousands of galaxies show structures whose sizes are comparable to the largest scales that have been studied. With the new instrumentation being developed for the 1990s, it will be possible to extend these measurements to even larger scales.

Within our own Galaxy, radio emission is observed from short-lived nonthermal stellar flares that are up to a million times more intense than those seen on the Sun. Radio observations of pulsars that have formed during the complicated evolution of interacting pairs of stars are teaching us important lessons about the last stages of stellar evolution. Measurements of the Zeeman splitting in OH and H_2O maser clouds are revealing magnetic field strengths in the regions surrounding both newly formed and very old stars. In the tenuous regions between stars, radio recombination line emissions from atoms with principal quantum numbers up to 700 have been observed from highly excited atoms with individual dimensions almost as large as a tenth of a millimeter.

Even within the solar system, radio observations have brought many unexpected discoveries, ranging from the solar radio bursts mentioned earlier to radio noise emanating from violent electromagnetic activity on Jupiter. Receivers have been built with continually improving sensitivity at ever higher frequencies, allowing radioastronomers to use thermal radio emission to determine the surface and subsurface temperature distributions of all the planets and many asteroids, satellites and comets and to deduce the constituents of the surfaces and atmospheres of all these objects. Of special interest has been the recognition of a runaway greenhouse effect on cloud-covered Venus, which causes the surface to heat up to 700 K. Passive radio measurements also show that the unlit side of Mercury, previously thought to be one of the coldest places in the solar system, is actually close to room temperature. Radar observations show that Mercury rotates about its axis and does not, as previously thought, keep one side perpetually turned away from the Sun.

Innovative uses of radiotelescopes

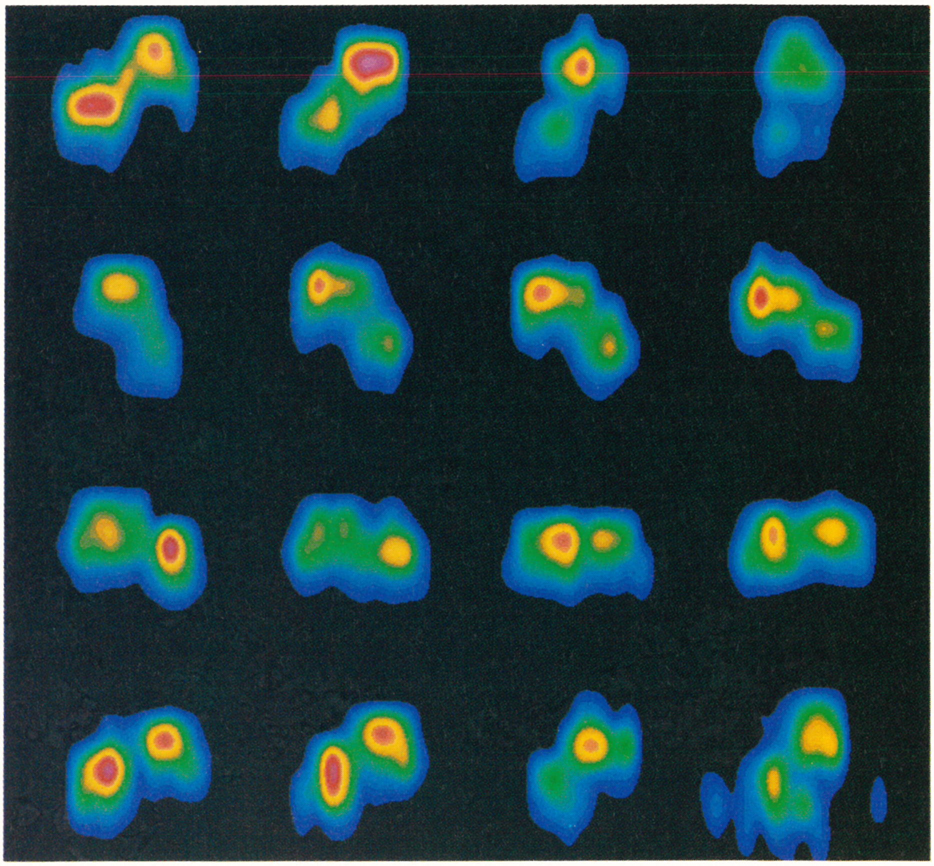
Radiotelescopes are also being used for a variety of experiments in fundamental physics and for important terrestrial applications:

▷ Observations of the orbital periods of binary pulsars provide the only experimental evidence for gravitational radiation.

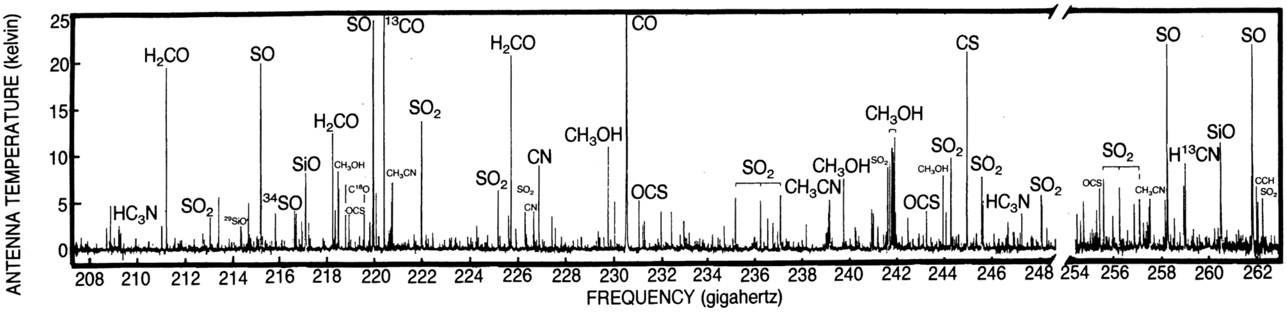
▷ High-resolution radio interferometers measure the relativistic bending of radio waves that pass close to the limb of the Sun; the accuracy is greatly improved over that of the classical light-bending experiment.

▷ Measurements of the time delay of radar signals reflected from Venus when those signals pass close to the limb of the Sun give a fourth test of special relativity.

▷ Very-long-baseline interferometry observations of distant quasars are being used to determine tectonic plate motions of a few centimeters per year on Earth, to provide the fundamental measurements of polar motion and Earth rotation used for terrestrial timekeeping, and to study the complex interaction between global atmospheric circulation and the rotation of the Earth. The potential application of radio interferometry to earthquake prediction has received great attention, particularly in "earthquake prone" countries such as Italy, China, Japan and the USSR, where extensive dedicated facilities are being



Asteroid 1989 PB. This sequence of 16 Arecibo Observatory radar images covers a bit over half of the object's 2.5-hour rotation period. (The sequence goes from left to right, top to bottom.) The images are derived from the time delays and Doppler shifts of radar echoes, and show the near-Earth asteroid to have two distinct 1-km lobes. The images were made when the asteroid was 3.4 million miles from Earth. (JPL–NASA photograph; courtesy of Steven J. Ostro.)



Millimeter spectrum of the Orion molecular cloud. More than 1000 lines have been identified with about 30 molecular species. High-resolution images of the chemical and isotopic distributions show the gradients of temperature and density, as well as the kinematics, within the cloud and give insight into the process by which molecular clouds collapse to form stars. (From G. A. Blake, E. C. Sutton, C. R. Masson, T. G. Phillips, *Astrophys. J.* **315**, 621, 1987.)

constructed for VLBI observations of tectonic plate motion.

▷ The search for extraterrestrial intelligence, although not really part of radioastronomy, uses instruments and techniques developed for radioastronomy. Radioastronomers pioneered the development of observational SETI programs. SETI is a powerful intellectual and technical challenge, and a successful "contact" would be one of the greatest events in the history of humanity.

Millimeter and submillimeter astronomy

During the past decade there have been particularly dramatic advances in technology at millimeter and submillimeter wavelengths. The planets, stars and galaxies all formed from cool matter that radiates most strongly at very short radio wavelengths. The millimeter spectrum of the interstellar medium rivals in richness the Fraunhoffer spectrum of the Sun and stars. The high spectral resolution of interstellar molecular clouds provided by radio spectroscopy can be used to determine the densities, temperatures, chemical compositions and isotopic abundances of clouds that range in size from that of planets to that of small galaxies.

Millimeter and submillimeter radiotelescopes with diameters of 10–20 meters are being operated at facilities throughout the United States, as are several millimeter interferometer systems. A 10-meters submillimeter telescope is being constructed in Arizona, and the Smithsonian Astrophysical Observatory is building the world's first submillimeter array. However, the largest millimeter radiotelescopes currently in operation are located in Japan and Europe.

In this country, the 42-m radiotelescope at the Haystack Observatory is being upgraded for operation at longer millimeter wavelengths. And a new, 100-m Green Bank telescope is being built to replace the 300-foot transit telescope that collapsed in 1988; it will have full sky coverage and an innovative design that includes an active surface with over 2000 independently adjustable panels to permit operation down to at least 7-mm wavelength.

The Millimeter Array

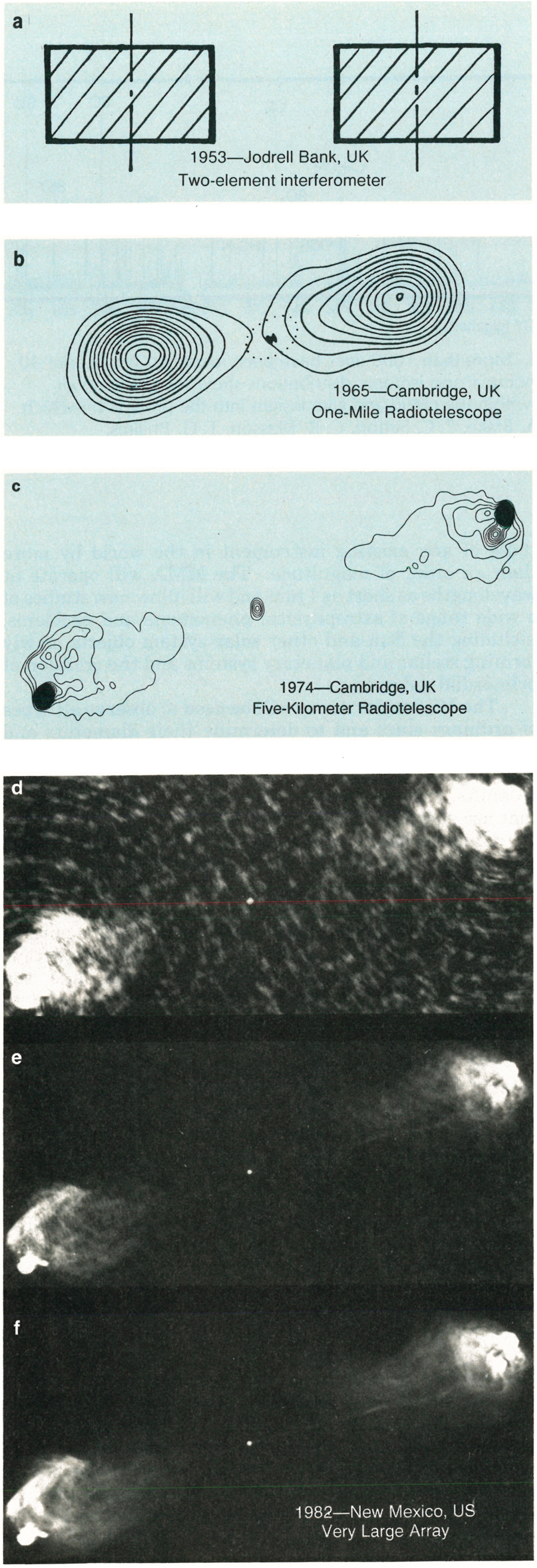
To fully exploit the opportunities for research at millimeter wavelengths, radioastronomers have developed plans for a large Millimeter Array that will have a sensitivity, resolution, speed and image quality exceeding those of any existing instrument in the world by more than an order of magnitude. The MMA will operate at wavelengths as short as 1 mm and will allow new studies of a wide range of astrophysical phenomena and problems, including the Sun and other solar system objects, newly forming stellar and planetary systems and the creation of primordial galaxies.

The Millimeter Array will be used to observe all types of ordinary stars and to determine their diameters and temperatures. It will also image the emission from dust and carbon monoxide in galaxies out to very large redshifts, and will observe the nuclei of distant galaxies that are obscured at other wavelengths.

High-resolution millimeter-wave observations of the Sun and planets will also be important for the study of a variety of phenomena that cannot be observed in other parts of the spectrum, even from spacecraft. The MMA will be able to detect the high-energy particles that emerge with new solar flares, to study the physics of particle acceleration, to observe atmospheric winds and the temperature distributions on Mars and Venus, and to investigate the exotic conditions found in Jupiter's Great Red Spot and Io's volcanoes.

The Astronomy and Astrophysics Survey Committee considers the timely construction of the Millimeter Array as a national facility to be the highest priority for new instrumentation in radioastronomy. However, because the MMA will take at least a decade to complete, it is especially important that adequate support also be given to the millimeter and submillimeter telescopes that are currently in operation or under construction. These instruments will advance the science and technology during the next decade and will serve as training grounds for the young scientists who will use the MMA. The university-based millimeter interferometers will play a particularly important role because the scientific and technical program leading to the MMA was initiated and will continue to be developed at these facilities.

One of the most dramatic developments in radioastronomy has been the extraordinary improvement in the angular resolution of radiotelescopes, which now exceeds by orders of magnitude that of telescopes operating in any other wavelength band, whether in space or on the ground. This has been possible because at radio wavelengths the atmosphere does not introduce the distortions that have limited ground-based optical instruments to a resolution



Radio galaxy Cygnus A. These successive interferometric images of the radio galaxy demonstrate the improvement in resolution and image quality of radiotelescopes over a period of about 30 years. **a:** In 1953 it could be determined only that the galaxy has two main lobes about 2 arcminutes apart. **b:** Radiotelescope with two fixed and one movable antenna shows more detail. **c:** Array with four fixed and four movable elements reveals central component and "hot spots" in the lobes. The three images at the bottom are based on observations made in 1982 with the 27-element Very Large Array. **d:** Unprocessed image contaminated by spurious responses of the VLA. **e:** Deconvolution with a maximum-entropy algorithm provides the Fourier components missing from the incompletely filled array and removes most of the spurious features. **f:** Self-calibration corrects for the different gains and atmospheric delays at each antenna element.

only a little better than a second of arc. High resolution is achieved at radio wavelengths by using interferometric techniques, in which the effective resolution corresponds to the spacing of the individual antennas rather than to their size. Sophisticated techniques and algorithms have been developed to correct for the incompletely filled arrays and the effects of the Earth's atmosphere and thereby produce remarkably detailed radio images.

By far the most powerful and productive radiotelescope in the world is the 27-element Very Large Array in central New Mexico. This instrument, which was built during the 1970s on schedule and at the budgeted cost, is now used by more than 500 astronomers each year for a wide range of astrophysical problems. The VLA exceeds its design specifications in speed, sensitivity, resolution, image size, image quality and the number of frequencies at which spectroscopic observations can be made simultaneously. However, during the past decade it has not been possible to provide the refurbishment and upgrading that an instrument of this sophistication and scientific value needs. Because there have not been adequate funds for even the most basic maintenance, the railroad track, power distribution system, antenna structures and other parts of the physical plant are deteriorating.

The Astronomy and Astrophysics Survey Committee recommends that over the next decade, the 15- to 20-year-old instrumentation of the VLA be upgraded with modern technology. This will improve the sensitivity by up to an order of magnitude and will improve the frequency coverage and spectral resolution. The AASC also recommends that the VLA be expanded by building up to four new antenna elements to give enhanced resolution and imaging capability over a wide range of frequencies and surface brightnesses.

Very-long-baseline interferometry

For dimensions exceeding a few tens of kilometers it is impractical to connect the elements of an array directly. The Very Long Baseline Array, now under construction, was recommended by the 1982 Astronomy Survey Committee, which gave it the highest priority for a major new telescope for ground-based astronomy (see Patrick Thaddeus's article in PHYSICS TODAY, November 1982, page 36). However, because the annual funding has been at a much lower level than originally planned, the construction time has been extended from four years to nearly a decade.

The VLBA will use tape recorders and independent hydrogen-maser frequency standards instead of a direct physical connection between the ten elements of the array, which are located from the Virgin Islands to Hawaii. All of the antenna elements will be controlled from a combined VLA–VLBA operating center in Socorro, New Mexico, where the tapes from each antenna also will be simultaneously replayed and analyzed to form images. The VLBA will give the highest angular resolution of any astronomical instrument and will be used for high-resolution studies of active galactic nuclei, quasars, interstellar masers and radio stars; for the direct determination of distances throughout the Galaxy and to nearby galaxies; and for a variety of applications in geodesy and geophysics.

We can improve resolution further by extending interferometer baselines into space. A communications satellite in NASA's Tracking Data Relay Satellite System has already been used in conjunction with ground-based radiotelescopes to demonstrate the feasibility of very-long-baseline interferometry in space with baselines longer than two Earth diameters. Both the USSR and Japan are planning to launch dedicated VLBI satellites in the mid-1990s for high-resolution imaging of quasars, active galactic nuclei and interstellar masers. The AASC recommends that support be given for US astronomers to participate in these novel experiments.

A next-generation space VLBI mission, the International VLBI Satellite, is being discussed by European, Soviet, Japanese and American radioastronomers. The plan is to use a powerful Soviet Energia rocket to launch a 25-m-class antenna to altitudes between 20 000 and 150 000 kilometers. IVS, which will work to wavelengths as short as 3 mm, will provide a further order-of-magnitude improvement in sensitivity and image resolution over the Japanese and Soviet missions planned for the mid-1990s, but developing this expensive mission will require the combined resources of many countries.

Support

Because the atmosphere is largely transparent at radio wavelengths, radiotelescopes are built on the ground, where construction and operating costs are very much less than in space, and where it is easier to exploit new technology. Except at very long wavelengths, where the ionosphere becomes opaque, or for special experiments, such as space VLBI, it is not necessary to place radiotelescopes in the more difficult and costly space environment, and radioastronomy has developed essentially as a ground-based science. For this reason, the total expenditure for astronomy at radio wavelengths has been significantly smaller than that for any other wavelength range, even though the wavelength range covered by radiotelescopes is comparable to the uv, optical and infrared bands combined.

Following the Second World War, government research laboratories and a number of universities established radioastronomy programs, largely with support from the Department of Defense. When NSF was established, it supported radioastronomy through the creation of the National Radio Astronomy Observatory and through research grants to university scientists. Following the passage of the Mansfield Amendment, NSF absorbed the university radio observatories that DOD had helped to establish, and NSF is now the primary source of support for all radioastronomy in the United States. However, for more than a decade now, NSF funding has not kept pace with the rapidly growing needs of ground-based astronomy. This has had particularly serious consequences for radioastronomy, which is almost totally dependent on NSF for the support of individual scientists; for the operation, maintenance and upgrading of existing radiotelescopes; and for instrumentation and computing resources.

Unlike the postwar years, when radioastronomy was done largely by researchers with backgrounds in radio science, today a broad spectrum of university-based scientists and their students are using radiotelescopes. The university radio observatories provide an environment that encourages experimentation and the active participation of students and postdocs, but often they are not competitive with large national and international facilities in other countries. The NSF-funded national centers for radioastronomy were established to give university researchers access to powerful radiotelescopes that are too expensive and complex to be operated by a typical university research group. The instruments at the National Radio Astronomy Observatory and the National Astronomy and Ionosphere Center's Arecibo Observatory are the most powerful and sophisticated facilities of their type in the world and are available to scientists independent of their institutional affiliations or nationalities. Research programs at these national radioastronomy centers are carried out by the observatory staffs and by small groups of scientists, or even by individual scientists who visit from their home universities for short periods, typically a few days.

The long-term health of radioastronomy in this country requires a proper balance between the large, unique facilities at the national centers and the smaller, but often also unique, facilities where many important discoveries are being made, where innovative techniques are being developed and where the next generation of observers and telescope builders is being trained. ■