

This paper serves as an introduction to the following papers, which were presented at a colloquium entitled “Quasars and Active Galactic Nuclei: High Resolution Radio Imaging,” organized by a committee chaired by Marshall Cohen and Kenneth Kellermann, held March 24 and 25, 1995, at the National Academy of Sciences Beckman Center, Irvine, CA.

Quasars and active galactic nuclei: High resolution radio imaging

MARSHALL H. COHEN* AND KENNETH I. KELLERMANN†

*Department of Astronomy, California Institute of Technology, Pasadena, CA 91125; and †National Radio Astronomy Observatory, Charlottesville, VA 22903

The 12th colloquium in the series organized by the National Academy of Sciences, *Quasars and Active Galactic Nuclei: High Resolution Radio Imaging*, was held at the NAS Beckman Center in Irvine, California, on March 24 and 25, 1995. The meeting brought together 138 scientists from 17 countries. The majority of the participants were *radio astronomers*, the colloquial name for astronomers who specialize in studies at radio wavelengths. However, there was also a strong mixture of theorists and other astronomers who work primarily in other wavelength bands, and this provided lively discussion and an occasional healthy dose of skepticism.

Since radio waves are longer than visible light waves by a factor of about 10^5 , it was widely believed, for many years, that the angular resolution of radio telescopes is fundamentally poorer than obtained by optical telescopes. For several reasons, however, this is not the case, and the resolution of radio images now often exceeds the best images obtained by optical telescopes. The main reason is that, in practice, the resolution of conventional ground-based optical telescopes is restricted not by diffraction, but by atmospheric *seeing*, which limits the angular resolution, even on the best high-altitude sites, to about 0.5 arc sec. Seeing constraints are eliminated by going to space, but only at very great cost. Technical and cost constraints limit the size of telescopes in space, so that even the refurbished 2.4-meter Hubble Space Telescope has an angular resolution only somewhat better than 0.1 arc sec, less than a factor of 10 improvement over the best ground-based images.

At radio wavelengths seeing usually has a negligible effect, and diffraction-limited resolution is possible. Structural limitations, however, restrict the maximum dimensions of conventional filled-aperture steerable antennas to about 10^4 wavelengths, or to a resolution of about 1 arc min, approximately that of the unaided human eye. Much higher angular resolution is achieved by using radio interferometers with widely separated antenna elements, since the angular resolution is given by the reciprocal of the array size measured in wavelengths. With separated antennas, diffraction-limited performance can be obtained over essentially unlimited distances, and a major thrust throughout the history of radio astronomy has been meeting the technical challenges of building interferometers of ever-increasing dimensions.

For modest distances, the array elements are interconnected with wires, waveguide, or more recently, with fiber optic cables, and the signals from the individual elements are combined in “real time” in a large correlator. Digital computers then are used to Fourier transform the correlator output to produce the radio image, to correct for small residual errors due to the finite number of elements used to synthesize the large aperture, and to remove the remaining small effects of atmospheric phase fluctuations. The largest system of this type is the 35-km-wide Very Large Array (VLA) located on the Plains of

San Augustin in central New Mexico. The 27-element VLA has an angular resolution of about 0.1 sec of arc at its shortest operating wavelength of 1.3 cm, better than that achieved with any ground-based optical telescope.

Even higher angular resolution is obtained by using radio links to connect antennas spaced by more than a hundred kilometers. The Multi-Element-Radio-Linked-Interferometer-Network (MERLIN), operated by the Nuffield Radio Astronomy Laboratories in the United Kingdom, achieves an angular resolution better than 0.1 arc sec at centimeter wavelengths, but for many studies this is still inadequate. The Universe contains many types of objects—such as quasars, active galactic nuclei (AGN), interstellar molecular masers, and stellar radio sources—which are wildly out of thermodynamic equilibrium. The nonthermal radiation from these objects comes from regions which are exceedingly small, and far beyond the resolution limits of any conventional radio or optical telescope on the ground or in space.

In order to study these very compact radio sources, a wireless version of interferometry was developed in the 1960s. In this system of very long baseline interferometry (VLBI), the signals are recorded on magnetic tape at each antenna element, and the tapes are then sent to a central station for processing. Atomic clocks are used to synchronize the tapes and to maintain coherence among the individual antenna elements which may be separated by thousands of kilometers. There are no interconnecting wires and, of course, the system does not operate in real time, for at a minimum there is a delay in transporting the tapes to the central correlator. In addition to astrophysical studies, VLBI has many applications to precision astrometry, geodesy, and geophysics, and it is being actively investigated in a number of countries as a means of earthquake prediction.

VLBI has developed as a major international enterprise for both astronomical and terrestrial investigations, with as many as 15 or 20 antennas throughout the world being simultaneously used to image radio sources with angular resolutions better than a milliarc second, orders of magnitude better than any other telescope operating on the ground or in space. But many of the antennas used for VLBI are not optimally located for high-quality imaging, often do not work well at the short wavelengths, and are in demand for other radio astronomy observations. By the 1970s the need for a dedicated array of antennas which could be routinely operated as a single facility became apparent. Construction began on the Very Long Baseline Array (VLBA) in 1985. This recently completed telescope system consists of ten antenna elements located throughout the United States from the Virgin Islands to Hawaii. Control of the antennas and correlation of the tapes takes place from an Array Operations Center collocated in Socorro, New Mexico, with the VLA operations center. The

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Abbreviations: VLA, Very Large Array; AGN, active galactic nuclei; VLBI, very long baseline interferometry; VLBA, Very Long Baseline Array.

VLBA, as well as the VLA, is operated as a national facility by the National Radio Astronomy Observatory under a cooperative agreement with the National Science Foundation. The timing of the colloquium was arranged to permit the incorporation of results from the new VLBA in addition to VLBI studies made using existing global arrays of radio telescopes.

The earliest VLBI experiments used only two antennas and could measure only a crude diameter for each source. Nevertheless, the first experiments showed directly that the very small sizes inferred for the quasars and AGN were real, and that they could be understood within the framework of conventional incoherent synchrotron radiation from relativistic electrons moving in weak magnetic fields. Variable radio sources were studied intensively, partly because it had been predicted that bulk relativistic motion was needed to avoid the effects of inverse Compton cooling of the radiating electrons. Apparent faster-than-light motions were discovered in the early 1970s and were referred to as *superluminal*. The appearance of superluminal motion is thought to be an illusion due to time compression caused by the relativistic motion oriented nearly along the line of sight. This gives an apparent transverse velocity which can be greater than the speed of light.

Another consequence of bulk relativistic motion is the Doppler boosting of the radiation along the direction of motion, which may cause an enhancement of the apparent luminosity by more than a factor of a thousand. Through this effect, the apparent morphology of a radio source can depend dramatically on orientation. The so-called *unified models*, which attempt to interpret the wide variety of morphological structures seen in galaxies and quasars as the effects of orientation, formed a major theme of the colloquium.

Hundreds of radio galaxies and quasars have now been studied by VLBI and classified into various morphological categories, and the first paper, by Wilkinson (1), reviews the status of this work. Readhead (2) discusses a possible evolutionary scheme for radio galaxies and quasars as they grow in size. Zensus *et al.* (3) and Giovannini *et al.* (4) review the structure of the very powerful and low luminosity radio sources, respectively. Romney *et al.* (5), Biretta and Junor (6), Jauncey *et al.* (7), Bartel *et al.* (8, 9) and Krichbaum *et al.* (10) give the latest data on selected radio sources which are characteristic of the different types of radio galaxies and quasars studied by VLBI.

Several dozen superluminal sources are now known, and their collective properties may give information on cosmology, in addition to information on the physics of the nuclei of galaxies. Vermeulen (11) reviews the statistics of these sources and their potential for future research. A new discovery, reported by Taylor *et al.* (12), shows motion in both the approaching and receding components of a symmetric quasar. This is important because observations of two-sided motion may ultimately be used to set the distance scale of the universe, independent of the hierarchical arguments needed in more conventional discussions of the distance scale.

Rodriguez and Mirabel (13) report the dramatic discovery of a superluminal source within our own Milky Way Galaxy. Because it is nearby, changes in apparent position of the components can be seen with the VLA from one day to the next. The opportunity to study in detail the relativistic ejecta from the central engine in these nearby low luminosity sources will give added insight to understanding the physics of their much more powerful extragalactic counterparts.

The papers by Gabuzda (14), Gopal-Krishna (15), Singal (16), Laing (17), and Saikia (18) discuss the radio evidence for unified models. Miller (19) broadened this discussion by including the evidence for anisotropic optical emission from quasars and AGN partially obscured by a surrounding dusty torus.

VLBI observations have been crucial to the understanding of the maser emission from dense molecular clouds of hydroxyl

(OH) and water vapor found in the interstellar medium surrounding very young and highly evolved stars. This work was not covered in the colloquium except for the exciting report by Moran *et al.* (20) of high-velocity rotation of water maser sources located within half a light year of the nucleus of the galaxy NGC 4258. Analysis of the dynamics shows that this galaxy contains a central mass of about 36 million times the mass of the sun, characteristic of black holes widely postulated, but never observed, to exist at the centers of active galaxies. The extraordinary resolution of the VLBA gives a lower limit to the central mass density of a galaxy which is far greater than has been established by any other means. The NGC 4258 VLBI observations are recognized as the most convincing evidence yet found for the existence of a supermassive black hole in the center of a galaxy.

Hewitt (21) reviews the effect of gravitational lensing on images of extragalactic radio sources, while Marscher (22) and Begelman (23) discuss the interpretation of the radio, x-ray, and γ -ray emission and the nature and collimation of relativistic jets in quasars and AGN.

The conference concluded with an inspiring summary by Philip Morrison and a stimulating panel discussion by R. Ekers (Chair), R. Antonucci, G. Burbidge, R. Fosbury, P. Morrison, S. Phinney, M. Rees, P. Scheuer, and M. Urry. Geoffrey Burbidge gave a thought-provoking dinner address reminding the participants that there is still a lot that we don't know and of the dangers of concentrating on currently popular themes in science.

The conference was organized by a small scientific organizing committee consisting of M. Cohen (cochair), K. Kellermann (cochair), R. Ekers from Australia, R. Fosbury from Germany, and M. Rees from the United Kingdom. All papers presented at the colloquium were invited and were chosen by the Scientific Organizing Committee to be representative of the most exciting work being done on high resolution radio imaging of quasars and AGN. In order to benefit from the broad expertise of the other participants, all papers published in these *Proceedings* have been reviewed by one of the participants as well as the editors. Also, to expedite scientific interaction between the authors and referees, the referees were not anonymous, and they interacted directly with the authors, exchanging manuscripts and comments by electronic mail from all corners of the globe. We thank the referees—Z. Abraham, R. Antonucci, P. Barthel, J. Biretta, R. Blandford, R. Booth, I. Browne, T. D. Jones, P. D. Murphy, D. Osterbrock, T. Muxlow, R. Schilizzi, G. Setti, P. Scheuer, T. Tzioumis, M. Urry, I. Pauliny-Toth, T. Pearson, R. C. Walker, J. Wardle, A. Werhle, and J. Wrobel—and the authors for agreeing to this arrangement and for their cooperation in completing the manuscripts in a timely way.

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