18 June 1982, Volume 216, Number 4552

SCIENCE

Radio Astronomy with the Very Large Array

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The largest ground-based astronomical instrument ever built has now been completed on a 2100-meter plain in New Mexico. The instrument is called the Very Large Array (VLA) because it consists of 27 radio antennas spread in various sizes of Y-shaped configurations up to 35 kilometers in maximum extent. It is the most advanced instrument in radio astronomy. Funded by the National Science Foundation and built and operated by the National Radio Astronomy Observatory, the VLA is primarily an instrument for making two-dimensional images of astronomical sources of radio emission (*1*). It can produce images of radio sources with a resolution comparable to or better than that of the best ground-based optical telescopes.

Summary. The construction of the Very Large Array of radio telescopes has been completed, and this new research instrument is now being used to make radio images of astronomical objects with a resolution comparable to or better than that of ground-based optical telescopes. The role of the Very Large Array in current and future research is discussed both in principle and in terms of a sample of observing projects.

Figure 1 shows several VLA antennas, a small section of the railroad track system for moving antennas, and the antenna assembly and maintenance building. The inner and outer portions of the array are schematically shown in Fig. 2, where one can see the relationship of the antenna stations, the twin railroad track antenna transportation system, and a waveguide communication system that allows operational control and data acquisition by computers in the control building.

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Why the Very Large Array?

All sciences are fundamentally rooted in observation and experimentation. Astronomy outside the solar system is founded solely on observations of astronomical sources of radiation (electromagnetic) and matter (cosmic rays) reaching the earth. Because the earth's atmosphere is transparent to radiation mainly at optical (29 to 120 micrometers) and radio (1 centimeter to 100 meters) wavelengths, ground-based astronomy—and indeed all of astronomy—is dominated by observation in these wavelength ranges. The angular resolution (θ) of any telescope is fundamentally determined by the ratio of the wavelength L of the radiation and the size of the measuring instrument D, namely $\theta = L/D$.

Historically, optical observations have been the foundation and main support of astronomy. If one wishes to do radio astronomy with a resolution comparable to that at optical wavelengths, the radio instrument must be larger than the optical instrument by the ratio of their wavelengths, roughly 10,000. Large optical telescopes have optics with dimensions up to meters in size, so a radio instrument with comparable resolution must have dimensions of tens of kilometers. Radio antennas on this size scale cannot be constructed on the surface of the earth. Fortunately, electronically linked antennas with tens of kilometers of separation can be used as a single instrument to accomplish radio observations with a resolution which sometimes exceeds that possible with optical telescopes. The VLA is an array of 27 antennas, each with a surface 25 m in diameter, linked by a waveguide system along each of the three arms of a Y-shaped configuration. The four possible configurations for the antennas correspond to the range of sizes 1, 3.5, 10, and 35 km, so one can obtain comparable resolution for the four primary wavelengths, 1.3, 2, 6, and 21 cm. All antennas are movable and can be operated from any of the 72 three-piered concrete stations. They are moved by the antenna transporters along the twin railroad track system every few months to form one of the four standard antenna configurations. The antennas were assembled from prefabricated sections in the maintenance building (Fig. 1) between 1975 and November 1979.

Principle of Aperture Synthesis

The VLA parameters were established by the principal design goal: to build an instrument that would have variable, high-resolution capability for all accessible regions of the sky. In particular, this requirement set the number of antennas, their location along the arms of a Y-shaped railroad system, and the typical mode of operation by which radio sources to be mapped are tracked across the sky as the earth rotates. The basic principle of operation, called aperture synthesis, was pioneered by Sir Martin Ryle. Aperture synthesis is based on the fact that the cross-correlation of signals between any two antennas i and j is a measurement of a complex visibility that can be expressed, in a two-dimensional approximation valid under most circumstances, as

$$V_{ij}(u,v) = \int \int I(x,y)\, f(x - x_0,\, y - y_0) \times \exp[-2\pi i(u_{ij}x + v_{ij}y)]\; dx\, dy \qquad (1)$$

where $I(x,y)$ is the intensity distribution of radio emission on the sky as a function of sky coordinates x and y, $f(x-x_0, y-y_0)$

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is the antenna sensitivity function when pointing at and tracking a sky position (x_0,y_0), and u_{ij} and v_{ij} are two coordinates describing the separation of the ith and jth antennas as seen by an observer located in the sky at (x_0,y_0). The measured complex visibilities are basically a two-dimensional Fourier transform of the radiation distribution on the sky weighted by the antenna sensitivity pattern, which localizes the observed radiation to the area of the sky covered by the antenna beam. Furthermore, since we know the sensitivity pattern for each antenna, Eq. 1 means that with a sufficient number of measurements of $V(u, v)$, one can reconstruct an image of the radio emission in the antenna beam by using the properties of Fourier transformation, namely

$$I(x,y) = \frac{1}{f(x - x_0, y - y_0)} \int \int V(u,v) \times \exp [2\pi i(ux + vy)]\, du\, dv \qquad (2)$$

The quality of images reconstructed from the numerical equivalents of Eq. 2 is determined by a combination of the quality of individual visibility measurements and the completeness of the sampling of (u,v) points inside the area of maximum radius D. Figure 3 shows plots of sampled (u,v) points as seen by an observer located in the sky at the position of a source at different declinations (angular distances from the projection of the earth's equator on the sky northward to the location of the radio source), assuming all 27 antennas of the VLA observe the source continuously from horizon to horizon. These are pictures of the "aperture" being synthesized by the VLA. The trade-offs between cost and sampling with as many antennas as possible resulted in the design compromise of 27 antennas in a Y-shaped configuration with sampling capabilities as shown in Fig. 3. An ideal instrument would have completely uniform sampling within a specific area.

Table 1. VLA observing frequencies and associated spectral lines.

Possible frequencies (GHz)	Protected* frequencies (GHz)	Atomic and molecular lines
1.34 to 1.73	1.40 to 1.427	Neutral H: 1420.4 MHz H, He, and so on: recombination lines $HCONH_2$ (formamide): 1538 to 1542 MHz OH: 1612, 1665, 1667, and 1721 MHz HCOOH (formic acid): 1639 MHz
4.5 to 5.0	4.99 to 5.0	$HCONH_2$: 4617 to 4620 MHz OH: 4660, 4751, and 4766 MHz H_2CO (formaldehyde): 4830 MHz H, He, and so on: recombination lines
14.4 to 15.4	15.35 to 15.40	H_2CO: 14.489 GHz H, He, and so on: recombination lines
22.0 to 24.0	23.6 to 24.0	H_2O: 22.235 GHz NH_3: 22.834 to 23.870 GHz

*Frequencies specifically allocated for radio astronomy by international treaties.

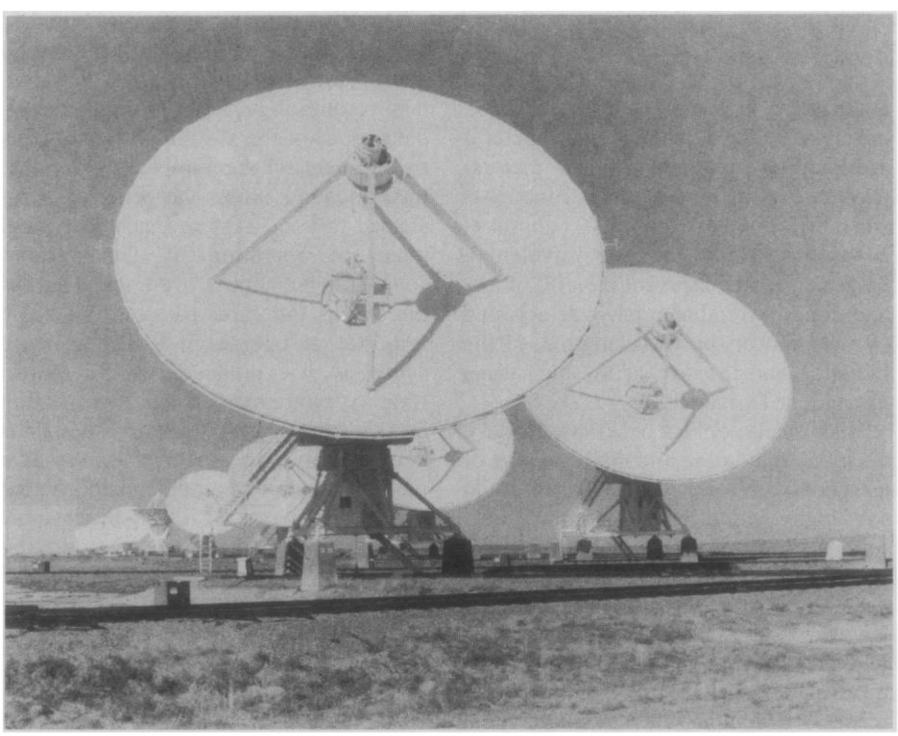


Fig. 1. Photograph of the inner portions of the array which gives close-ups of the antenna station piers, the railroad track system, and some of the antennas. The rectangular building in the background is the antenna assembly building and the view is to the southwest.

Antennas and Electronics

During the years between first conception and final construction, the modes of operation of the VLA were made more complex by adding capabilities to accomplish most of the conceivable types of observations at centimeter wavelengths. This has resulted in an instrument that can switch rapidly (in tens of seconds) between the principal wavelength bands and tune to any frequency for observation of spectral lines, such as those listed in Table 1. As seen in Fig. 3, each antenna consists of a collecting surface with a nearly parabolic cross section, which focuses radiation on a rotatable, hyperbolic surface subreflector that is held in position by four support structures. Rotation of this subreflector under computer control results in focusing the radiation to one of the (currently) four feeds that collect at the 20-, 6-, 2-, and 1.3-cm wavelengths. The feeds transmit the observed radio signals to electronics in a room built under the surface of each antenna, where the cryogenically cooled electronics amplify, carry out various frequency selection processes, and convert the signals to antenna-dependent frequency regimes. These signals are sent up and down the waveguide of each arm in the array for nine antennas. During one out of every 52 milliseconds the signals in the waveguide are antenna and electronics control signals sent from the control computers in the control building, and during the other 51 msec they are signals containing astronomical information sent from each antenna to the electronics systems in the control building. The signals from each of n (=27) antennas are converted to the same frequency range and, after insertion of delays that compensate for the different times of arrival at different antennas, the signals for all $n(n-1)/2$ (=351) antenna pairs are multiplied (cross-correlated) and averaged over 10 seconds to produce measurements of complex visibility functions. Once all the observations of a particular radio source are stored in the off-line computer system (and on magnetic tape), the astronomer uses an extensive set of computer programs to apply known corrections, carry out an empirical calibration, compute the radio images by using the properties of Eq. 2, and display the results.

Extragalactic Radio Sources

It is not possible here to fairly summarize the hundred or so VLA observing programs that are carried out each year; however, the real reasons for building and using an instrument like the VLA are found only in the reasons for carrying out these observing programs. In this and the following sections we will therefore briefly discuss a sample of VLA observing programs.

The primary motivation for many of the U.S. astronomers who conceived the VLA was the mapping of radio sources associated with distant galaxies. The primary advantages of the VLA over present arrays in England and the Netherlands are a wide range of resolutions, including fine resolution hitherto unavailable, a greater ability to detect weak radio emission, greater flexibility, and a greatly improved imaging capability over the sky north of −48° declination. Maps of extragalactic radio sources have been one of the main products of the VLA ever since it became possible in 1977 to map sources with more than several antennas.

The radio source 3C388, mapped by Burns and Christiansen (*2*) (Fig. 4), shows some of the principal features of large extragalactic radio sources. At the center of a large ellipical galaxy there is a core radio source whose dimensions are about one-fourth those of the surrounding double or lobed radio source in Fig. 4. The bright features in the lobes that curve back toward the central source are rudimentary versions of the "jets" that are found in many radio sources. These jets are a visible manifestation of the channeled regions through which the central portions of the galaxy supply energy for the magnetic fields and relativistic electrons whose interactions produce the observed radio emission by synchrotron radiation processes. Detailed mapping of the intensity and polarization structure in extragalactic jets has been and is one of the main types of VLA observing programs.

The imaging capability of the VLA at low declinations is greatly improved over that of previous instruments because of the Y-shaped distribution of antennas. The 20-cm radio image of a radio galaxy at a declination of −42° has been mapped by Ewald (*3*) and is shown in Fig. 5. The observations were taken with the 3.5-km configuration of the VLA in August 1980. The x in Fig. 5 corresponds to the location of a large ellipical galaxy that is the brightest member of a rich cluster of galaxies. The large radio structures to the east and north of the galaxy are typical of the so-called

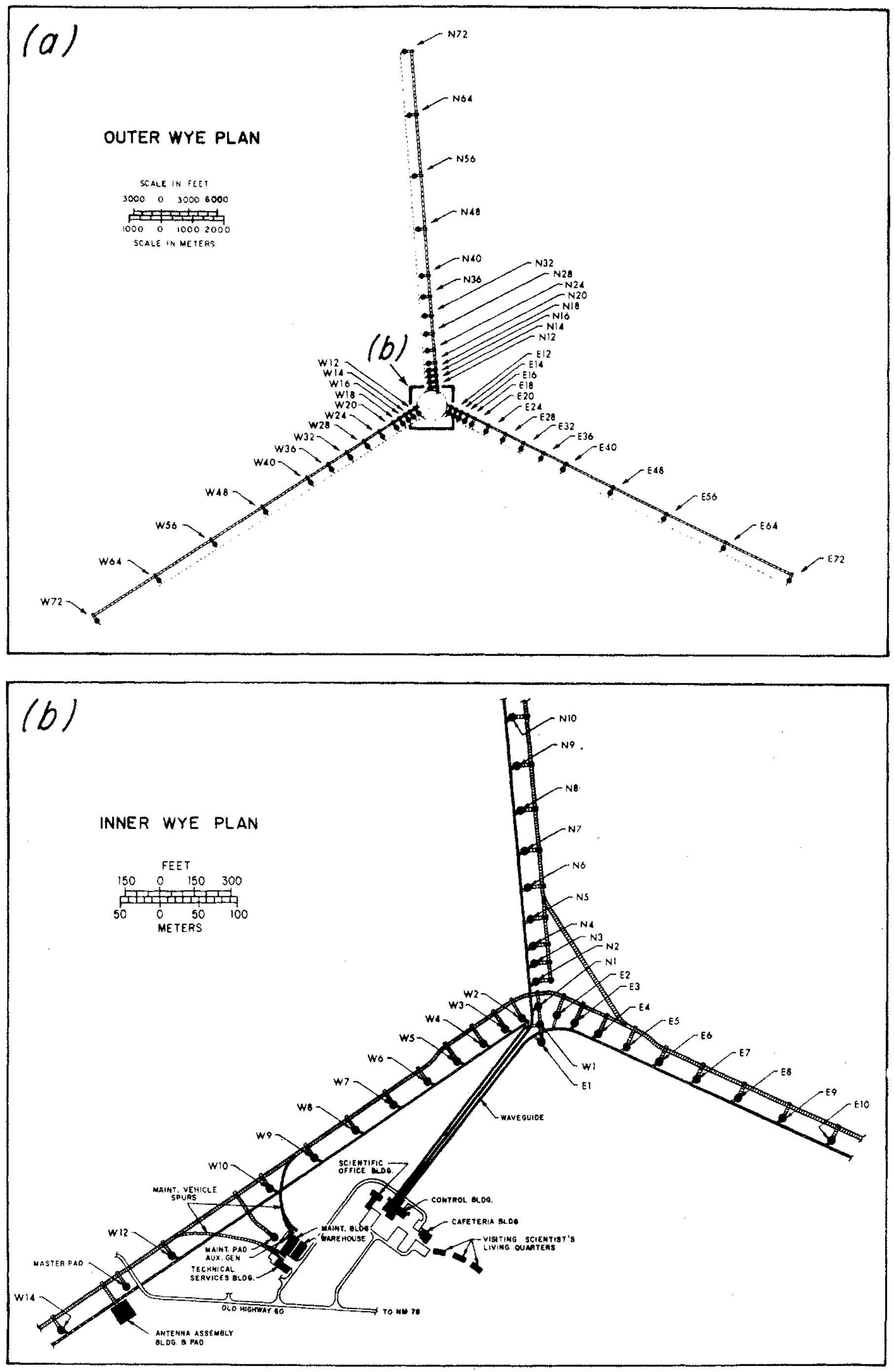


Fig. 2. (a) Schematic diagram of the outer stations of the Y-shaped (*wye*) VLA array. The circles show antenna stations, the dashed line shows waveguide locations, and the solid lines correspond to the railroad track system. The designations Xnn are station identifiers; $X = N$, W, and E for the north, southwest, and southeast arms and nn = station numbers. (b) Inner portions of the VLA showing buidings, roads, stations, the rail system, and the waveguide runs for each arm connected to the control building.

head-tail radio sources. Such radio tails are commonly interpreted as due to radio-emitting material that is ejected from the center of the galaxy and swept back by the dynamical interaction with the gas through which the galaxy is moving. Polarization maps of such radio sources reveal details about their magnetic field structures. Illustrating the need for the various sizes of the VLA, the extended structure in Fig. 5 is properly mapped only in the smaller configurations, whereas the small structures existing in the "head" of such head-tail radio sources can only be mapped with the larger configurations of the VLA.

The high resolution of the VLA is being utilized by many observing programs searching for and mapping the small structures of radio sources associated with quasars. Many of these obser-

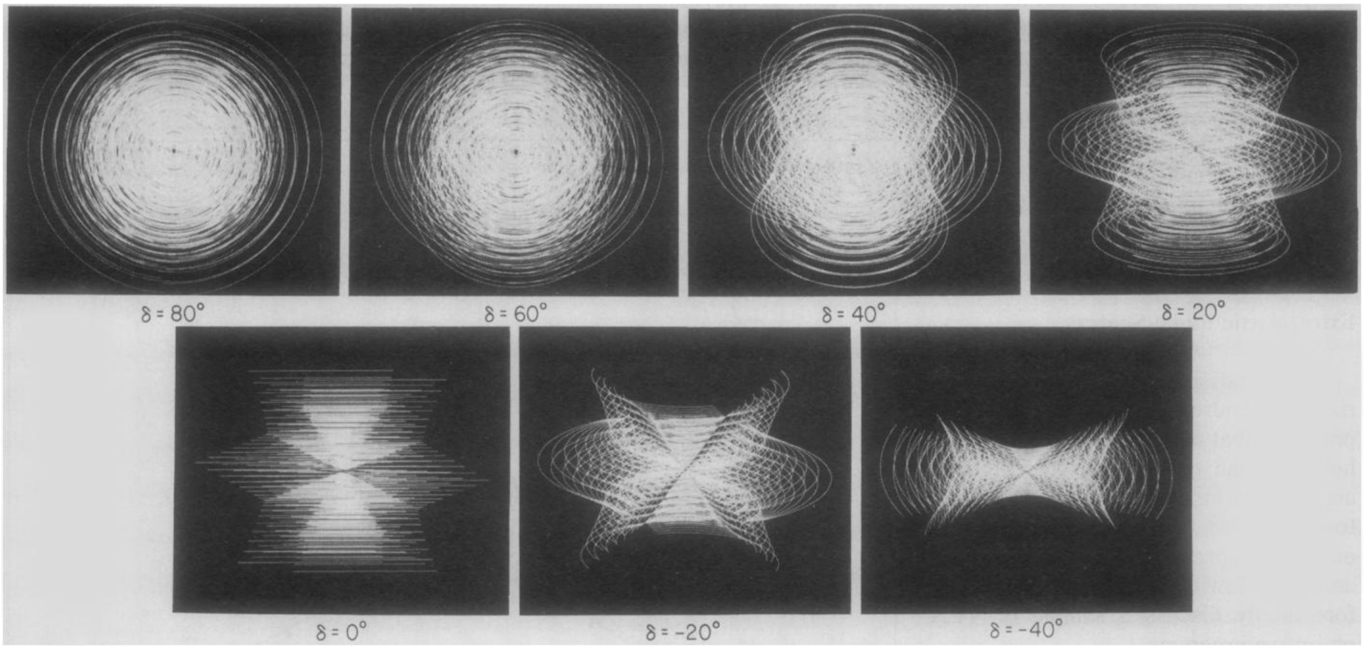
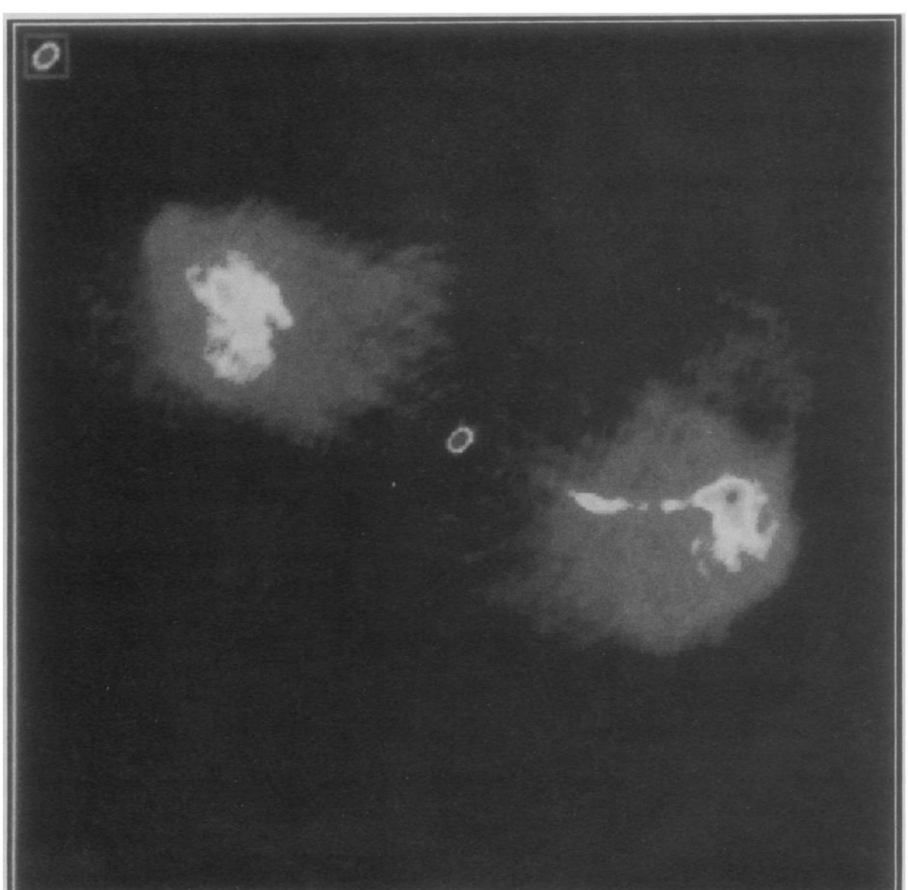


Fig. 3. Computer simulations of the telescope aperture synthesized for horizon-to-horizon VLA observing at a number of declinations. Each panel consists of all or part of 351 ellipses, each ellipse being the projection of a different antenna pair separation on the sky. Different positions along each ellipse correspond to different times of observation.



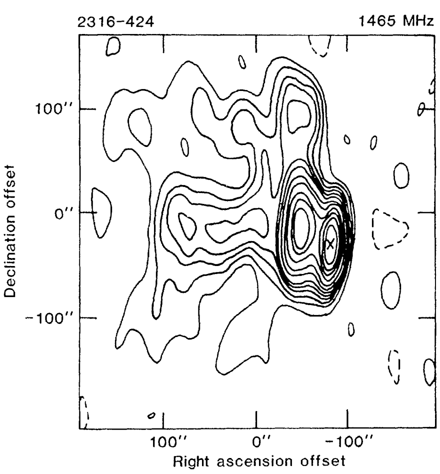
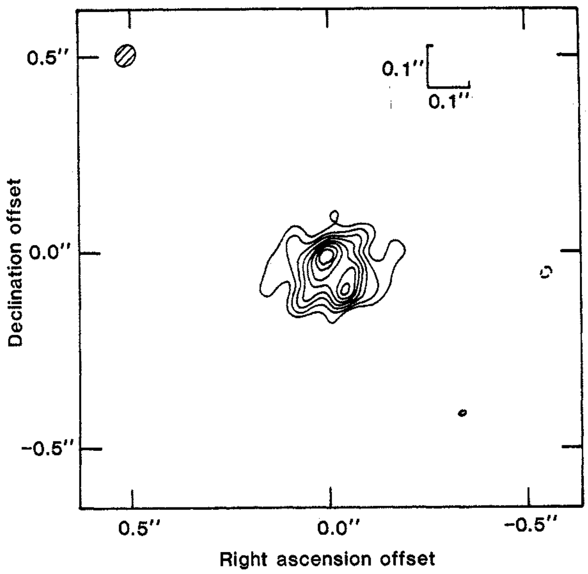


Fig. 4 (left). Radio image of the extragalactic radio source 3C388 at 20 cm as obtained by Burns and Christiansen (*2*). The appearance of a point source is indicated inside the box in the upper left corner. Fig. 5 (above). The "head-tail" radio source 2316-424 as mapped by Ewald (*3*) at 20 cm. With a declination of −42°, it is an example of the good imaging characteristics of the VLA at very low declinations.



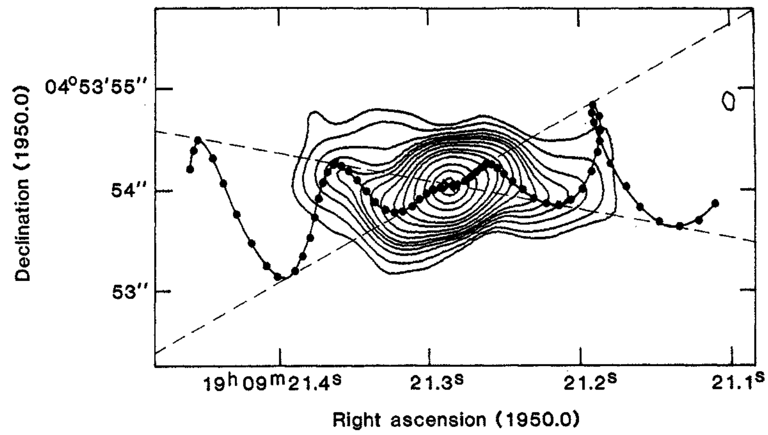


Fig. 6 (left). A 1.3-cm radio image of the stellar wind associated with the star V1016 Cygni as mapped by Newell (*4*) with the largest (35 km) configuration of the VLA. This is an example of the high resolution in a VLA radio map, which cannot be obtained with ground-based optical telescopes because of the effects of the earth's atmosphere. Fig. 7 (right). Contour map of the radio source associated with the star system SS 433. The map was obtained in 5 minutes of observation at 6-cm wavelength with the largest configuration of the VLA on 4 December 1980 by Hjellming and Johnston (*5*). The corkscrew indicates the observed paths of motion due to the 164-day period of rotation of the twin-jet ejection vector about the central axis. The filled circles are located at intervals of 10 days in time of ejection from the center.

vations indicate that the only differences between quasar radio sources and radio sources associated with galaxies are their size scale. Jets seem to be a very common component of quasars, and one of the principal puzzles they introduce is the common occurrence of one-sided jets.

Radio Emission Associated with Stars

There are several types of stars in our galaxy which have observable radio emission. In some of these objects the high-resolution capabilities of the VLA now give astronomers the opportunity to map radio structures produced by stars and stellar systems.

The ultimate resolution possible with the VLA is obtained by mapping objects with the 35-km array at 1.3-cm wavelength. Such a map of the stellar winds surrounding the star V1016 Cygni, obtained in December 1980 by Newell (*4*), is shown in Fig. 6. This source was previously interpreted as one where thermal radio emission is produced by an ionized and massive stellar wind, and the VLA radio map shows that such stellar winds can have complex structure. With levels of detail of this type, one discovers that either there must be two interacting winds or the observed radio emission is due to a nova-like ejection of material into a previously existing stellar wind. The principal structures in V1016 Cygni are qualitatively similar to the equatorial ring and polar "blob" structures of nova shells.

A more exotic example of a radio source associated with a stellar system is SS 433. Figure 7 shows a VLA map of SS 433 made at 6-cm wavelength on 4 December 1980 by Hjellming and Johnston (*5*). The remarkable structures associated with this object change on time scales of a week or two. The radio emission is caused by synchrotron radiation from relativistic electrons and magnetic fields generated by a central star system. SS 433 has become famous in recent years (*6*) for the optical jets seen in the form of intense emission lines which indicate matter moving both toward and away from the earth with speeds that are projections of a total speed of one-fourth the speed of light. Changes in the apparent speeds of motion have been used to derive parameters of a twin-jet model in which the jets rotate with a period of 164 days about the jet axis.

Detailed structures in the radio jets of SS 433 are found to move outward from the star with an angular speed of 3 arc seconds per year. Hjellming and Johnston (*5*) showed that all the structures in maps of SS 433 at different times lie on a "corkscrew" pattern on the surface of a cone with an axis at a position angle of 100° oriented 80° from the line of sight. The conical surface is 20° from the cone

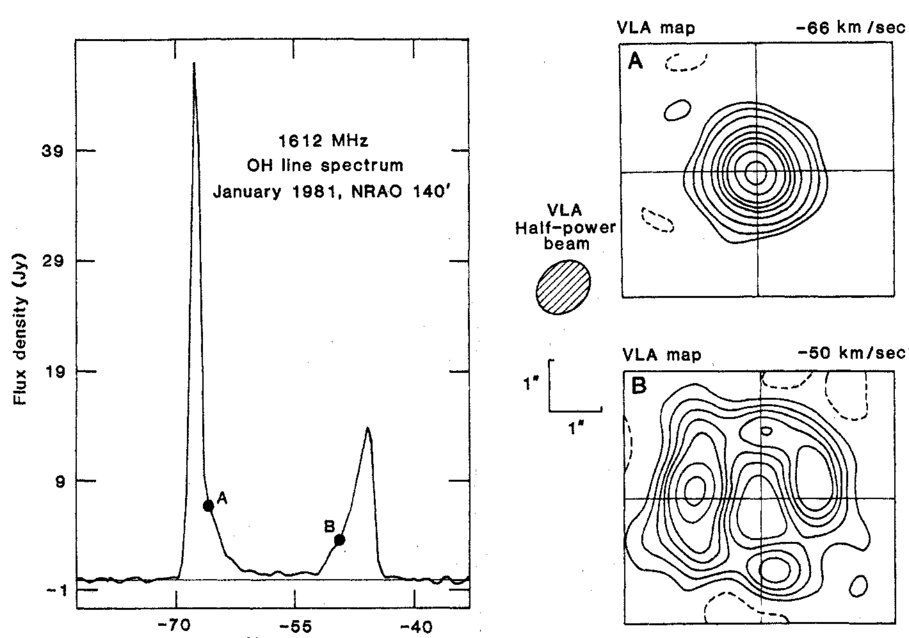


Fig. 8. The OH line spectrum of the star OH127.8-0.0 plotted as a function of velocity with respect to the local standard of rest (LSR), together with VLA maps made at specific frequencies corresponding to −66 and −50 km/sec by Bowers *et al.* (*7*).

axis, and the corkscrew pattern is achieved because the oppositely directed ejection vectors rotate with a period of 164 days. The corkscrew pattern for 4 December 1980 is superimposed on the radio map in Fig. 7. Because of time travel effects across the source, the apparent corkscrews of SS 433 are perceptibly "distorted" in a way that allows absolute determination of the velocity of motion. This velocity turns out to be one-fourth the speed of light, and all the geometric parameters of the rotating corkscrew match the parameters of the optical jets of SS 433. Thus the radio jets are additional observable manifestations of the moving material emitting optical lines very close to the star system, probably due to flows perpendicular to a precessing accretion disk.

One of the capabilities of the VLA which has become fully believable only with the completion of the instrument is the power of a single short observation or "snapshot." The map of SS 433 in Fig. 7 was made from data taken during a single 5-minute period. More extensive observations produce only small degrees of improvement, although they are essential for detecting the weakest levels of radio emission. The snapshot mode of observing makes it possible to map hundreds of strong sources in a day. Many observing programs can therefore be carried out in only an hour or two of scheduled observing. Because of this, many more scientists will be able to use the VLA in a given period of time than would have been possible without such a large number of antennas.

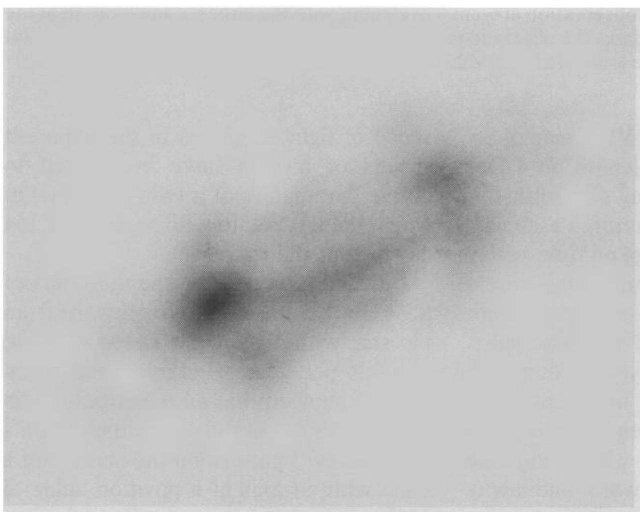


Fig. 9. Radio image of Jupiter and its radiation belts obtained by Roberts *et al.* (*8*) at a wavelength of 20 cm.

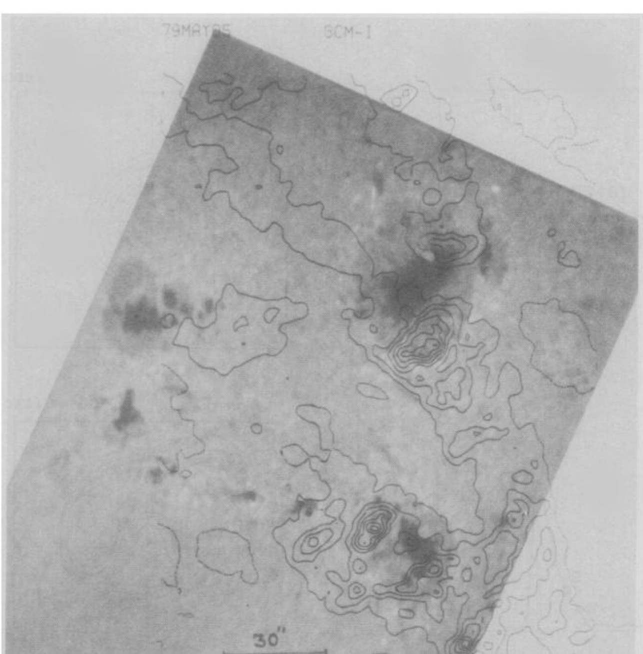


Fig. 10. Contour map of active regions on the sun made on 5 May 1978 at 6 cm by Velusamy and Kundu (*9*), superimposed on an optical picture taken in the Hα line by R. Robinson of Sacramento Peak Observatory.

Observations of Radio Spectral Lines

Many atomic and molecular spectral lines can be observed with the VLA, some of which are listed in Table 1. In Fig. 8 a portion of the spectrum due to the 1612-megahertz line of the OH radical is shown, in addition to two high-resolution VLA maps made at different frequencies from data obtained by Bowers *et al.* (*7*). The 1612-MHz line is spread out in frequency due to line-of-sight Doppler shifts of the emitting material. In this case the OH emission is maser radiation coming from an expanding cloud of gas around a red giant star that is undergoing extensive mass loss. For a saturated maser like this, the amplification at a given velocity depends on the path length over which the velocity variation along the line of sight is very small. The peak feature in the spectrum in Fig. 8 is material approaching us on the near side of the star, and the second strongest feature is material on the other side of the star moving away from us. The weakness in the emission between these two features is due to the large velocity spread of matter moving perpendicular to the line of sight. The result is that the VLA map of the approaching material (velocity of −60 km/sec) shows the more compact emission with high maser gain along the line of sight, whereas the map at −50 km/sec is mainly a map of the extended shell structure of OH-emitting material perpendicular to the line of sight. The results shown in Fig. 8 are only a small fraction of the data from which the OH maser shell can be constructed in great detail. This provides specific information about the expanding atmosphere around the star.

Although spectral line work played only a small role in the original arguments for building the VLA, observations of most of the spectral lines listed in Table 1 have shown that detailed mapping of spectral line emission will be a major task of the VLA in the coming years.

Solar System Observations

The high resolution and sensitivity of the VLA make possible new types of observations of solar system objects. A spectacular example of this is the mapping of the radiation belts surrounding

Jupiter. Shown in Fig. 9 is an early map of Jupiter made by Roberts *et al.* (*8*). The thermal emission from the central disk of the planet is clearly perceptible, and surrounding it is the nonthermal radio emission from Jupiter's radiation belts. These structures are analogous to the Van Allen radiation belts around the earth.

Observations of radio events on the sun with the VLA have been carried out by groups from the California Institute of Technology, the University of Maryland, Tufts University, and others. With the high resolution and high frequencies of the VLA solar radio astronomers can observe deep into the solar atmosphere to see radio emission associated with the sites of origin of major flares. A VLA radio map of a solar active region obtained by Velusamy and Kundu (*9*) is shown in Fig. 10. The radio contours are superimposed on an optical photograph in the hydrogen alpha line taken by R. Robinson at Sacramento Peak Observatory.

Among the many complex problems being investigated by solar radio astronomers with the VLA, there is one specific theme that occurs with great frequency. With the VLA one can make very good, high-resolution maps of potential flare sites. This makes it possible to locate and study radio emission from material participating in the motions and acceleration processes involved in the conversions of energy between magnetic fields and plasma which are basic to the physics of active regions and flare sites.

A final example of the use of the VLA in solar system studies is the observation of asteroids. C. M. Wade, K. J. Johnston, and P. K. Seidelmann are using the VLA to observe and track Ceres and other asteroids. This is one of few cases where both radio and optical emission are due to exactly the same (thermal) processes in the same physical regions. Thus successful simultaneous tracking of asteroids with the VLA and optical astrometric telescopes will allow the radio and optical observing reference frames to be established with respect to each other to high accuracy.

Future of Astronomy with the Very Large Array

In the survey above I have had to neglect the vast majority of scheduled VLA observing programs. An outline of these programs summarizes the expected role of the VLA in the coming decades. I have not discussed observations of comets, moons around solar system planets, ordinary stars, double stars, flare stars, pulsars, gaseous nebulas, novas, supernovas, supernova remnants, x-ray sources, interstellar molecules, interstellar neutral hydrogen, the structure of nearby spiral galaxies, supernovas and gaseous nebulas in other galaxies, or the full variety of radio phenomena in other radio galaxies and quasars. All of these have been and will continue to be observed by astronomers using the VLA. For astronomical observations at centimeter wavelengths and resolutions from 0.05 arc second to a few arc minutes, the VLA will probably continue to be the dominant instrument for at least the next two decades.

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Formaldehyde: A Question of Cancer Policy?

Frederica Perera and Catherine Petito

In what may constitute a test case for a new federal cancer policy, the Formaldehyde Institute, an association of formaldehyde producers and users, has advocated that formaldehyde not be regulated by the federal government despite recent studies showing that the substance causes tumors in animals and despite evidence that there is considerable human exposure to formaldehyde. The institute has argued that the animal data do not provide a sufficient basis to regard formaldehyde as a likely human carcinogen and that federal regulatory agencies should await the development of conclusive human (epidemiological) data before taking protective action.

This position contradicts principles for assessing carcinogenic risk that have been widely accepted by the scientific community for over a decade and embodied in policies of regulatory agencies following deliberations of broad-based scientific panels. These principles assert that confirmed positive animal data are presumptive evidence of carcinogenicity in humans; that with current information and methods it is not possible to establish threshold or no-effect levels that can be reliably applied to the human population; and that positive human epidemiological data are not necessary to conclude that a chemical substance poses a significant human risk (*1*). In fact, federal agencies have regulated such substances as pesticides, hair dyes, food additives, and industrial carcinogens (for example, β-propiolactone and ethyleneimine) in the workplace primarily on the basis of results in experimental animals (*2*). These principles are consistent with the accepted social policy that it is preferable to err on the side of caution in interpreting the available scientific data in order to avoid failure to regulate a serious health hazard.

Thus, acceptance by federal agencies of the industry position regarding the risk posed by exposure to formaldehyde could overturn established procedures for assessing and regulating carcinogenic

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