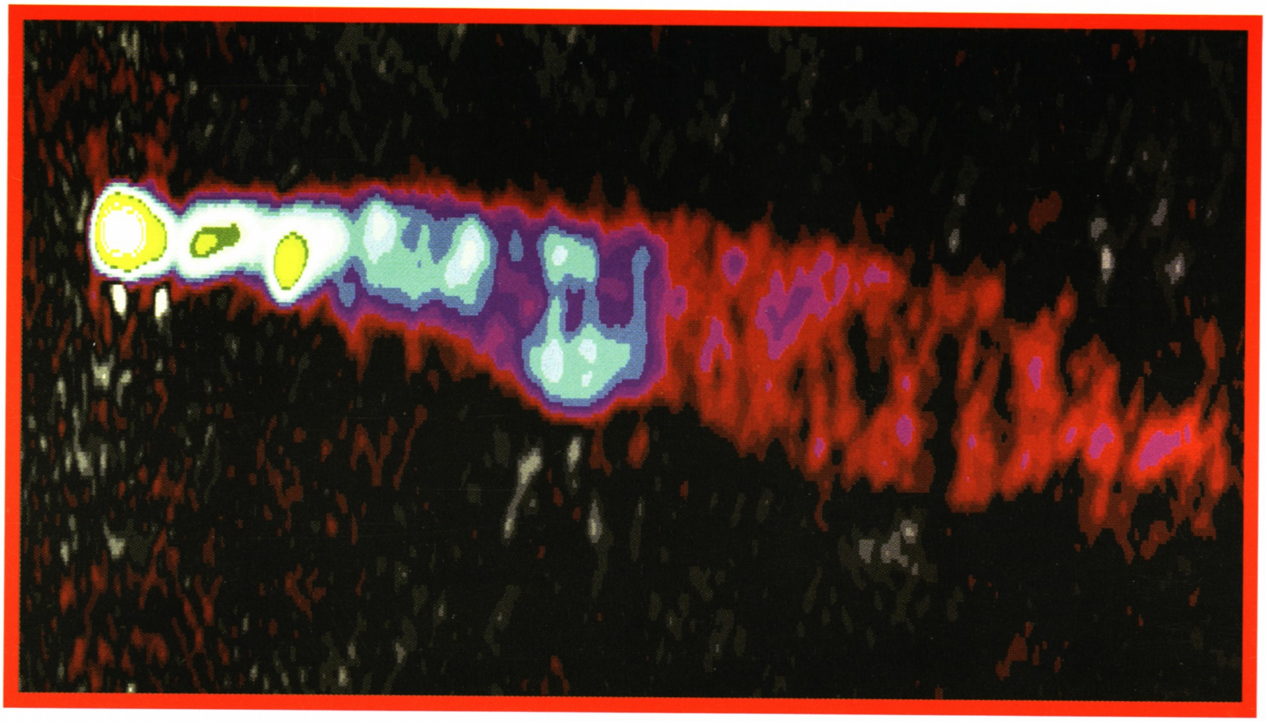

LONG RANGE PLAN
1997 - 2002

NATIONAL RADIO ASTRONOMY OBSERVATORY

Front of card: VLBA image of the radio jet at the center of the galaxy 3C120. Even at the great distance of this galaxy, 400 million light years from the Earth, the great resolving power of the VLBA makes it possible to image details as small as 1.5 light-years in size within the jet structure which is itself 100 light-years long. "Time-lapse" images made over several years show the jet to be moving outward at an apparent speed faster than the speed of light. Observers: R.C. Walker and J.M. Benson

NATIONAL RADIO ASTRONOMY OBSERVATORY

LONG RANGE PLAN

1997 - 2002

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I. OVERVIEW

In the period 1997-2002 the NRAO will complete the transition from an observatory that was founded to explore the question of whether radio astronomy could broaden our understanding of the universe beyond what could be learned at optical wavelengths, to an observatory that provides the foundation for the pivotal ideas of contemporary astrophysics. During the next five years all of the pioneering telescopes at the NRAO that were designed to survey the scope of radio astronomy will have been supplanted by modern telescopes and synthesis arrays. The new telescopes are designed to provide astronomers with detailed astrophysical knowledge that complements and extends understandings gleaned from the most advanced ground-based and space telescopes operating at other wavelengths. Realizing the new facilities as fully functional research instruments is the goal of the NRAO long range plan.

Figure I-1 on the accompanying page is an illustration of the many scientific achievements that are now becoming possible with modern instrumentation. Shown in this figure are two spectral absorption lines from molecular gas in a galaxy at a redshift of 0.9 that is seen along the line of sight to a distant background quasar. The chemistry of this gas, seen as it was nearly five billion years ago in a galaxy one-third of the way across the visible universe from us, is nearly identical to the chemistry in the Milky Way. The absorbing species we see in this figure are the same chemical species that we see in Milky Way molecular clouds. It suggests that the organic chemistry that is common on earth, and in the interstellar medium of the Milky Way, is also common throughout the universe and throughout the distant past. If we had such observations of many other galaxies we could confidently apply our understanding of chemistry, and the causal consequences of molecular chemistry such as star formation, elsewhere in the universe. But at present the telescopes are simply too limiting for this sweeping extrapolation. On the one hand, the VLA lacks the broadband receivers and wideband correlator needed for spectral study of redshifted cosmological objects. On the other hand, the older NRAO telescopes that have broadband receiving systems either have poor efficiency at high frequencies or have limited sensitivity owing to their small size. Advancements such as illustrated here were wholly beyond the realm of possibility when the current NRAO single-dish telescopes were designed and as a consequence they are poorly suited to the needs of this and other contemporary research endeavors.

The new instruments – the VLBA, the Green Bank Telescope, the Millimeter Array, and the upgraded VLA – are designed both with a recognition of the incredible breath of contemporary radio astronomical research and with the flexibility to respond appropriately to new scientific opportunities as discoveries are made. Each of these instruments are described in

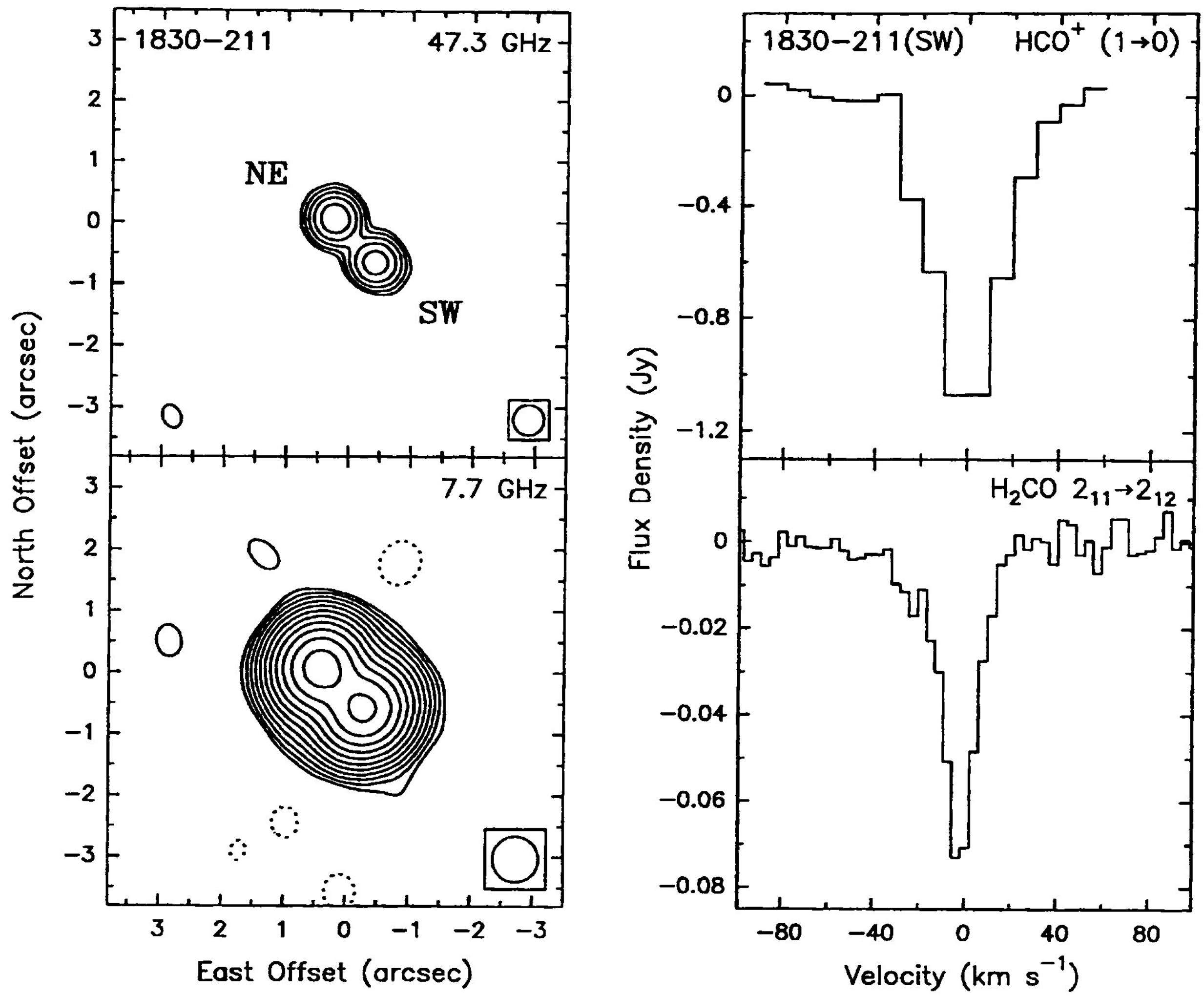


Fig. I-1. Absorption lines from the organic molecules HCO^+ and H_2CO have been detected at a redshift of 0.9 toward the gravitational lens system. Shown here are the VLA maps of the lens at 47.3 (upper) and 7.7 (lower) GHz and the absorption spectra at these two frequencies, respectively.

sections of this Long Range Plan. Together, they are the major component of NSF-supported ground-based astronomy.

The new telescope facilities require new and enhanced technical support. In Sections VI and VII, the electronics development and software/computing developments planned in support of the new instruments are outlined. In each of these cases the advancing technical state-of-the-art leads directly to scientific achievement. New instruments on new telescopes specifically designed for the new radio astronomical science leads to confident optimism about the future of radio astronomy at the NRAO. The operating budget and personnel projections required to sustain this future conclude the Long Range Plan.

II. THE GREEN BANK TELESCOPE

1. General Comments

In the first year of the present long range plan, the Green Bank Telescope (GBT) will become operational and the 140 Foot will cease operation as an NSF-funded facility. The GBT will not only replace the research functionality of both the older 300 Foot and 140 Foot Telescopes, but it has been designed to provide scientific opportunities far in excess of those available from the older facilities. In particular, the GBT will provide:

- full frequency coverage from 250 MHz to ~100 GHz;
- full sky coverage at high sensitivity;
- an unblocked aperture giving low sidelobes and high resistance to RFI;
- extremely wideband spectral analysis.

An artist's concept of the GBT is shown in Figure II-1.

Design of the GBT was driven by science requirements. For example, the desire of astronomers to use the sensitivity provided by the enormous GBT collecting area to detect the weak, broad, redshifted spectral line emission from cosmologically distant galaxies and quasars meant that the aperture could not be blocked by the subreflector and feed support legs. Having designed a clear aperture, however, and produced a clean beam with very low sidelobes in the process, the telescope can now be used to observe galactic HI with precision far greater than was possible with previous telescopes because the GBT HI spectra will be uncontaminated by stray radiation from the sidelobes. In designing a telescope to do the new science, we achieve also a telescope capable of doing on-going scientific investigations more capably.

2. GBT Science

The science program anticipated for the GBT is most naturally divided into five areas: stars, including pulsars, the sun, and the solar system; neutral hydrogen studies; spectroscopy; continuum radiation; and very long baseline interferometry. This research depends on the following features of the GBT.

- Sensitivity of roughly 2K Jy^{-1} will result in integrations of only minutes rather than the hours now required at the 140 Foot.
- Broad frequency coverage from 300 MHz to 52 GHz, eventually 100 GHz, gives the flexibility to observe at the frequency demanded by the science.

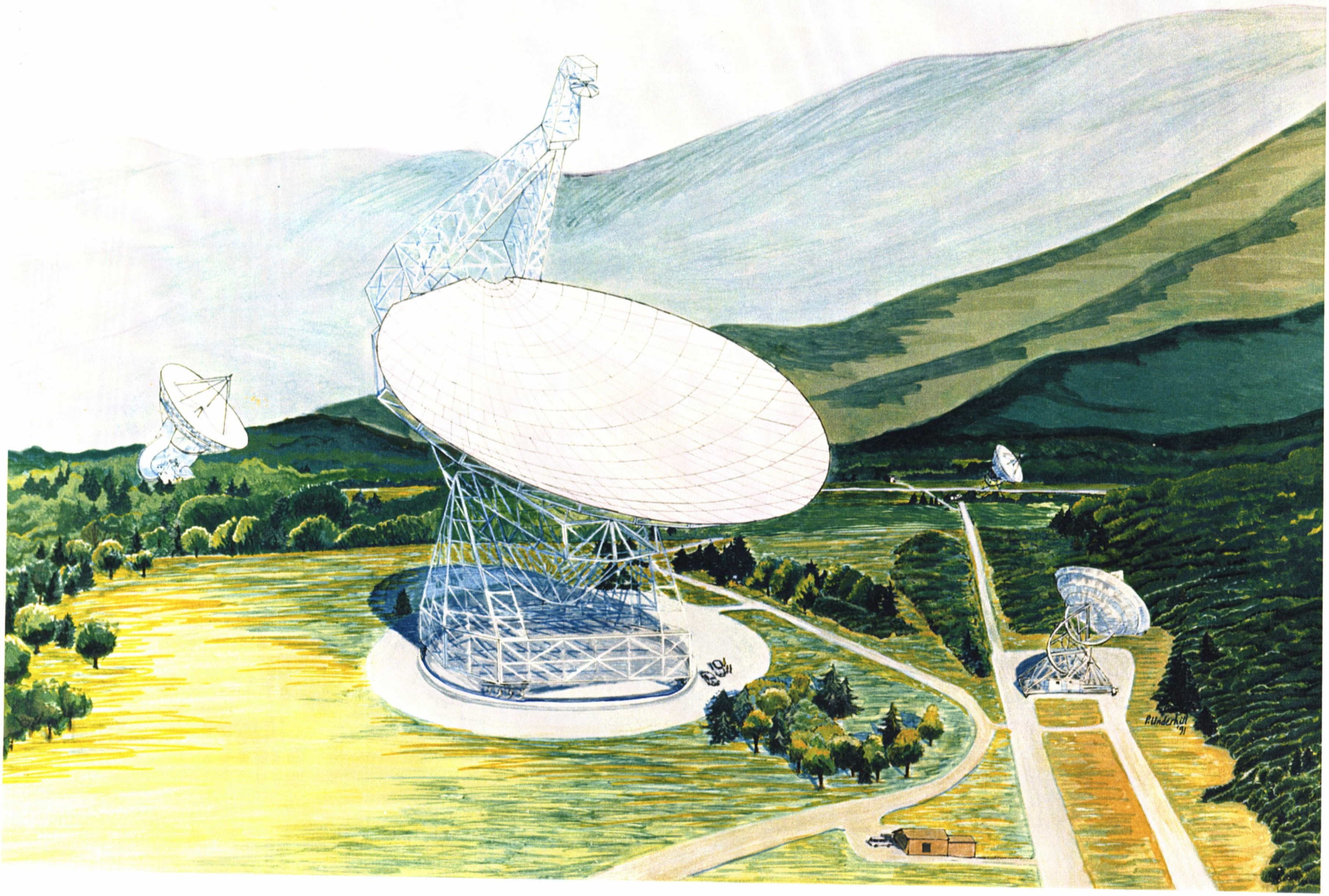


Fig. II-1. An artists concept of the Green Bank Telescope

- Unblocked aperture will yield superior spectral baselines and improved immunity to radio frequency interference. Stray radiation in galactic HI observations will be greatly reduced.
- Broadband spectrometer will make possible the simultaneous observation of several spectral lines, searches for lines of uncertain redshift or frequency, and the observation of lines expected to be very wide (*e.g.*, the fine structure lines of HI).

Pulsar timing will measure the gravitational radiation from close binary systems. A number of millisecond pulsars serving as clocks distributed along the ecliptic plane will be used to detect or set strong upper limits to long wavelength gravitational radiation originating at the Big Bang. Surveys of new pulsars, particularly in globular clusters, will increase the sample of known objects in the final stages of stellar evolution and will probe neutron star physics.

A great variety of radio stars will be detectable with the GBT. Broadband dynamic spectropolarimetry will be used to study thermal stellar winds, plasma effects in sunspots and in the intra-stellar magnetospheres of close binaries, and precessing radio jets fueled by accretion onto neutron stars or black holes. Multifrequency imaging of the Sun will help to define conditions in the upper chromosphere and transition region above coronal holes as well as in quiet and active solar regions.

The GBT will be sufficiently sensitive to detect HI emission from more than 10^4 galaxies distributed over 85 percent of the celestial sphere. Surveys for these galaxies will map the large-scale spatial distribution within $D \approx 100$ Mpc, as well as their motions relative to the smooth Hubble flow. The HI profiles of nearby galaxies also yield global properties (total mass, HI mass, mass-to-light ratio, surface density, etc.) which trace dark matter, reveal environmental effects, and show the effects of tidal interactions occurring in clusters or groups. In addition, protogalaxies and other gas-rich extragalactic objects of low optical luminosity will be detectable. The evolution of galaxies at high redshifts will be probed by observations of HI in absorption against distant continuum sources.

Within the Milky Way the 9 arcminute beam of the GBT at 21 cm will resolve structures as small as 20 pc at the distance of the galactic center. It will therefore be used to make HI maps of activity in the nuclear (central 1 kpc) region. The partition of gas between the spiral arm and interarm regions, HI envelopes around star forming molecular clouds and supernova remnants, and the flaring and warping of the galactic disk outside the solar circle are other likely areas of investigation.

The unequaled sensitivity, high resolution, and frequency agility of the GBT at short centimeter and long millimeter wavelengths will allow the detection of CO in starburst galaxies and quasars at cosmological redshifts (up to z ≈ 5), an important new field of study – the molecular content of galaxies from the epoch of galaxy formation. Multifrequency observations of CS, HC_3N, and CH_3OH transitions in the 30-50 GHz range will contribute to our understanding of molecular processes and provide the data needed for detailed multilevel models of density and temperature in the molecular clouds of our own and nearby normal galaxies. Spectroscopy of OH, H_2O, CH_3OH, and H_2CO masers will probe the kinematics and energetics of the most intense starbursts in the nuclear regions of galaxies.

In our own galaxy, maps of the stellar disk based on the 10^5 OH/IR stars detectable by the GBT will be combined with existing CO maps of the atomic and molecular gas disks. The structures of these disks perpendicular to the plane are the basic data needed to determine the total mass of the galactic disk, the existence or not of the thick disk, the nature and distribution of galactic dark matter, the history of star formation, the gravitational scattering of stars by molecular clouds, and the stability of molecular clouds to star formation. Both the physics and chemistry of the dense molecular clouds in which stars are born will be probed by multilevel spectroscopy of a wide range of molecules detectable in the $\lambda \approx$ 8 mm atmospheric window. The high sensitivity and resolving power of the GBT will be important for such studies. Detection observations seeking the weak deuterium line at 327 MHz and the $^3He^+$ line at 8.7 GHz will critically test various cosmic nucleosynthesis models.

The GBT will be able to make continuum sky maps covering ~10 steradians of the celestial sphere, with enough sensitivity and resolution to detect ~3×10^5 sources stronger than S ≈ 5 mJy at ν = 5 GHz. The maps will be used to discover intrinsically rare objects, to detect radio emission from nearby galaxies, to provide archival records of the radio sky at various epochs, and to permit comparison with sky maps in the infrared, optical, and X-ray bands.

Sensitive searches for primordial fluctuations in the cosmic microwave background radiation on 1-10 arcmin angular scales will be made, exploiting the high beam efficiency of the GBT. The telescope will be able to map temperature decrements in the microwave background produced by Compton scattering in the hot intracluster medium of rich clusters of galaxies (the Sunyaev-Zeldovich effect). This effect measures the intracluster medium's electron density and may eventually yield a direct measurement of the Hubble constant.

The GBT will be an important adjunct to the Very Long Baseline Array (VLBA) and Orbiting Very Long Baseline Interferometry (OVLBI) experiments because of its high sensitivity, frequency agility, and wide sky coverage. With the addition of the GBT, the VLBA will have the same collecting area as the VLA, permitting long, coherent integrations on weak sources – such as faint structures in superluminal objects, gravitational lenses, supernovae, radio stars, and extragalactic H_2O masers. Statistical parallaxes of H_2O masers will be used to measure the distances to maser sources in our own galaxy and to nearby external galaxies.

3. GBT Construction

By the second quarter of 1996, construction continued above the elevation axis on the box girder. The box girder is the framework which supports the backup structure, feed arm, and elevation wheel. It is the heart of the tipping structure. The forward and rear halves of the box structure have been completely trial erected on the ground. The box is being lifted in large, fully welded modules that facilitate erection. When complete, the box structure will be 140 x 163 x 40 feet.

Installation of the elevation wheel, which was trial erected at the plant in Mexia, Texas, is now complete. All eleven sections of the 91 foot radius wheel are in place. They have been aligned and welded along with the six large W19 beams which attach the el wheel to the shaft. All but six of the twenty-two counterweight boxes have been installed on the wheel. The boxes are approximately 14 x 8 x 8 feet and weigh about 25,000 pounds each empty, so installation was not trivial. Ultimately the boxes will be filled with concrete to counterbalance the structure with a weight of roughly 2 million pounds. The counterweight boxes will be filled in a predetermined order to keep the structure balanced during construction. The elevation gear has been installed and aligned and all eight of the elevation gear reducers with tangential links, backup rollers, and pinions are in place.

An assembly fixture, or jig, was built on site. The jig is approximately 175 feet long x 40 feet wide. It is being used for assembling and welding the large reflector rib trusses in a horizontal position. The jig is designed to maintain the critical surface curvature. As the trusses are completed, they are lifted off the jig and placed on the large concrete erection pad adjacent to the telescope site where the entire backup structure of the reflector will be constructed. Presently there are 21 trusses in place. For reference, there are 57 ribs total (the center rib plus 28 right and left). As the trusses are put in place each of the actuator support plates on the front chords are aligned optically from the 90 foot vertex tower. The assembly and trial erection of the backup structure (BUS) will continue throughout the remainder of 1996 and into the first quarter of 1997.

Following completion of the box atop the elevation wheel, the horizontal feed arm will be installed. With the horizontal feed arm and lower portions of the vertical feed arm successfully installed, erection of the BUS on the antenna may begin. The BUS modules will be disassembled from the trial erection pad and lifted into place on the antenna.

The feed/receiver room has been assembled and the feed turret, which will hold the Gregorian receivers and frontends, has been installed. Interior finishing of the room has been completed. The upper 60 foot portion of the vertical feed arm is being erected adjacent to the feed/receiver room.

All of the joints and beams required for the horizontal feed arm are on site; parts for the vertical feed arm are being fabricated as final drawings are received. The backup structure is made up of approximately 8000 individual parts. By the first of May, 4600 of these parts were on site. Finally, approximately 1200 of the total 2000 surface panels have been manufactured and are stored at COMSAT/RSI's plant in Sterling, Virginia. A recent construction site photograph is included here as Figure II-2.

4. GBT Schedule

Completion of the construction project and operation of the GBT as a radio telescope has been divided into phases for clarity and understanding. Phase 0 is the current construction phase and involves the construction and delivery of a fully operational antenna. It will be considered complete upon issuance of a provisional acceptance to the contractor by NRAO that the antenna and control system comply with the GBT contract specifications. The current schedule from the contractor calls for delivery on August 1, 1997.

During Phase I, the antenna will be transformed into a functioning radio telescope, complete with 2,200 active surface actuators (installed by the contractor during Phase 0), a local control center, an integrated monitor and control system, and a complement of primary and secondary feeds, receivers, back-ends, LO, IF, and cryogenics along with all associated interconnecting cabling. The performance of the Phase I telescope will be suitable for scientific operation up to 15 GHz.

Phase II will be complete when the active surface system is operational and can compensate for gravity deflections of the reflector surface as commanded by a computer program based on data provided by the contractor and verified by NRAO. It is planned that the laser ranger surface measurement system will become operational during this phase. The Phase II telescope will allow operation for scientific observations to frequencies as high as to 43 GHz.

Phase III will extend into the future and involves operation of the telescope at millimeter wavelengths. This will be accomplished using NRAO provided enhancements involving the laser ranger surface-measurement system and the precision pointing system which will take the telescope to its ultimate high frequency operation.

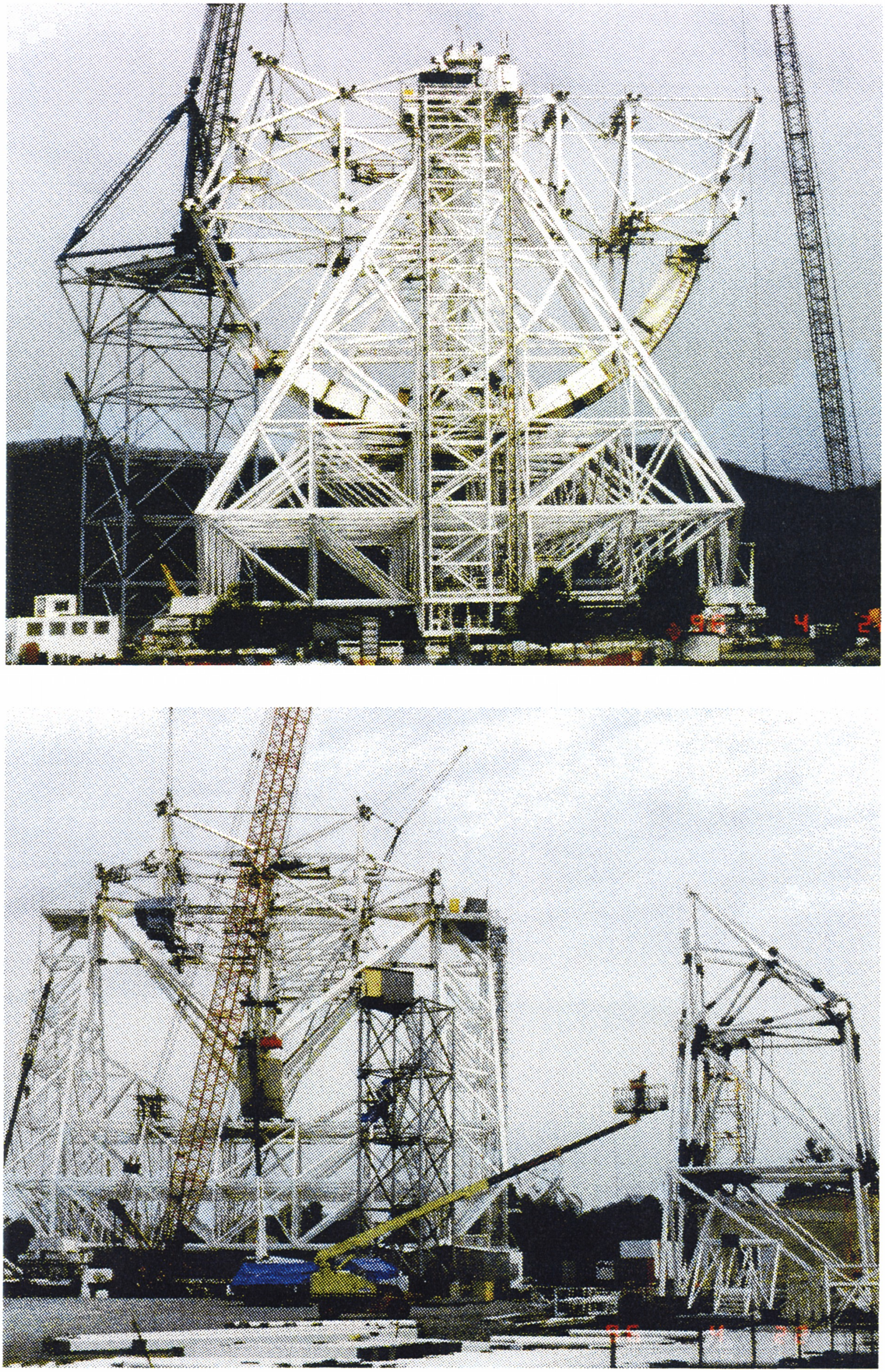


Fig. II-2. GBT construction site May 1996

5. GBT Operations

During 1997, GBT operations will begin, first in a debugging and test mode, then as a user facility in 1998. Operating the GBT will pose several challenges to the Green Bank staff. Unlike the 140 Foot Telescope, which is a mature and well-understood antenna that has been doing a relatively stable set of experiments, the GBT will be innovative and unique in almost all respects. Operations and maintenance procedures will have to be drawn up for the basic telescope, its drives and mechanical systems, as well as for subsystems like the active surface and the extensive set of metrology instruments. An unusually diverse group of backend detectors will be installed and operated. The suite of new receivers will have to be commissioned and understood. The monitor and control software system will be installed and used to coordinate all activities of the telescope. Moreover, there will be continuing development of new systems for the GBT over the next five years: new receivers, enhancements to the detectors, refinement of pointing and control, developments in metrology and software. Add to this the demands on data reduction hardware and software caused by the high data rate and great flexibility of the new equipment, and the need to assist the large group of inexperienced astronomers likely to use the new telescope, and the situation is one of unprecedented demands on the Green Bank staff.

The GBT will initially have seven receiving systems that cover much of the frequency range between 230 MHz and 26 GHz. Six of the receivers will be mounted permanently in the receiver room at the secondary focus, while the lowest frequency receiver will be installed in the prime focus boom. Additional receivers will be added at the rate of about one per year, gradually plugging gaps in the frequency coverage of the telescope. By the end of 2002 we hope to have virtually complete coverage of all frequencies between 25 MHz and 52 GHz. Higher frequency receivers are also under study, as are array receivers and multi-frequency systems. Each receiver that operates above 10 GHz will consist of at least two separate feed horns to allow rapid beam switching. A tertiary mirror system is now under development for the 40-52 GHz system. Once it is in successful operation, we will study the possibility of constructing additional tertiaries or other active optical components for use at lower frequencies.

Receiver Construction Schedule

Frequency (GHz)	Completion Date
0.3 - 1.2	Jan 1997
1.2 - 1.8	Jan 1997
1.8 - 2.6	Feb 1999
2.6 - 4.0	July 2000
4.0 - 5.8	July 1997
5.8 - 8.2	July 1998
8.2 - 10.0	Jan 1996
10.0 - 12.4	Feb 2003
12.4 - 15.4	Jan 1996
15.4 - 18.0	July 2002
18.0 - 22.0	Jan 1996
22.0 - 26.5	Jan 1996
26.5 - 33.0	Jan 2001
33.0 - 44.0	Jan 2001
40.0 - 52.0	July 2000

The optics systems on the GBT will present special operational challenges. The active surface alone has more than 2200 actuators, each with a motor and transducer. The 8 meter diameter secondary reflector is controlled by a 6-actuator Stewart platform that allows considerable flexibility of motion with highly accurate positioning, but which will pose interesting problems of calibration and maintenance. There will be at least one, and more likely several, tertiary mirrors in the optical path. Moreover, all receivers at frequencies above 10 GHz will be mounted in rotating assemblies that permit tracking at a constant parallactic angle. There may eventually be eight feed rotation assemblies. The roof of the Gregorian receiver room itself contains a large rotating turret which is used to position a receiver at the secondary focal point. All of these systems will give the telescope great frequency flexibility, allow numerous short projects to be interspersed, and make it possible to consider scheduling observing projects to match daily weather conditions. But the flexibility derives from complexity, and a lot of effort will be required to take advantage of all these potentialities.

The GBT will have a large number of detector backends that can be configured very flexibly to serve a variety of scientific programs. The 2048 channel spectral processor that is now at the 140 Foot Telescope will move to the GBT in 1997 where it will be used for pulsar measurements and for spectroscopy, especially below 1 GHz where its high dynamic range makes it resistant to interference. It has 8 IF inputs and can be configured in a number of modes. A 16-channel digital continuum receiver will be the backend most often used for continuum observing, such as pointing, flux density measurements, and mapping. Very long baseline interferometry will be supported by a VLBA data acquisition system so that the GBT can be treated as an element of the VLBA for purposes of data format and correlation. To match the extended frequency coverage of the GBT and its broad-band receivers, a 256k channel spectrometer is now under construction and may be available shortly after the GBT comes into operation. It will have a maximum bandwidth of 800 MHz, 8 IF inputs for its broader bands and 32 for its narrower bands. In addition to spectroscopy, the correlator can be used for pulsar searches and other pulsar observations. Its bandwidth, large number of channels, and flexible configuration will be ideally suited to redshift searches and simultaneous studies of numerous molecular transitions. In some of its modes the data rate from the new correlator will exceed that of our existing backends by many orders of magnitude and strain the Observatory's computational and data reduction resources. The correlator is well-matched to the GBT's new fiber optic IF system, which will have a bandwidth wide enough to cover the entire sky frequency range of virtually all receivers.

The GBT Correlator

Maximum bandwidth: 800 MHz
Samplers: 8 at 1600 MHz; 32 at 400 MHz
Total number of channels: 256k
Sensitivity: three level always; nine level at narrower bandwidth

The GBT has an extensive metrology program which holds the promise of being able to provide detailed information on the telescope surface and orientation in near real-time, allowing highly accurate pointing and surface adjustment. The NRAO metrology group has had to devise its own laser-ranging instruments for this task, and it is likely that this program will be in continuing development even as parts of it are put into application. The data from the metrology system consists of measurements of the precise location and orientation of up to several thousand points, including some key structural elements of the telescope. The system can measure the location of every surface panel, fiducial points around the dish edge, the subreflector, several points on the arm and the location of the arm with respect to the surface. It will also measure the position of the surface and arm with respect to a dozen fixed points on the ground. The synthesis of these data into a beam vector on the sky (i.e., the precise antenna gain and pointing) will require considerable research and field measurements over several years by a skilled team.

The scale and complexity of the GBT structure, metrology, and electronics systems require a software control system of comparable power. The monitor and control (M&S) software now under development by Green Bank staff uses the most modern software tools and advanced programming techniques to create an environment in which every critical component on the telescope is monitored and controlled. Monitor data (e.g., voltages and physical temperature of receiver components; wind speed and humidity; motor currents; phase delay through the IF lines) are stored in the same internal data format as astronomical data, so that standard data reduction tools can be used to analyze engineering and environmental information. Observers will have access to whatever data they think relevant for their science, and the GBT staff will have the ability to create and analyze data on instrument performance with an eye to detecting potential equipment problems before they occur. The M&C system is also being built with remote observing in mind, so that astronomers using the GBT, whether they are located at the Observatory in Green Bank or connected through the Internet from elsewhere, will have access to identical, complete, real-time information. The basic concepts behind the M&C software design have been proven in tests at the 140 Foot Telescope, and parts of the software have been in routine use for pulsar observations for more than a year. Development of further M&C tools, modifications for specific observing projects, and enhancements to cover new devices or operations modes will require the continued effort of Green Bank programmers.

The sheer size of the GBT requires new resources at Green Bank just for routine operations. The telescope will double the electric power load of the Observatory. It will have the largest emergency generators on site, which will require regular maintenance and testing. It will nearly double the number of elevators that have to be maintained. Its HVAC systems will add 50 percent to the site capacity. The maintenance load rises in proportion. Special devices (large cherry pickers, etc.) will be needed just to provide access to the structure for inspection and repair. Faulty elements of the active surface will need to be identified and replaced. The large number of receivers being kept online at any time places extra demands on the cryogenics systems. It is estimated that one person will be needed full time just to coordinate maintenance activities at the telescope.

Visiting scientists will require extra support to become familiar with the telescope and its new receivers, detectors, and software. The expected increase in demand for remote observing will mean that Green Bank computer staff will have to iterate development of appropriate controls, display, and feedback to observers. Telescope operators will take on greater involvement with and responsibility for the detailed execution of observing programs. Local scientific staff will have to be intimately involved with every experiment until the new modes of observing are fully developed. Observers will face unprecedented data rates when on-the-fly mapping techniques are implemented with the 256k channel spectrometer. In sum, for efficient and successful operation of the GBT the Observatory will have to commit significant additional resources to development of new GBT systems with consequent major enhancements of its scientific capabilities through the next five years. The budgets to support this growth are included in the NRAO long range plan summarized in Section VIII.

III. MILLIMETER ASTRONOMY: THE MILLIMETER ARRAY AND THE 12 METER TELESCOPE

1. The Millimeter Array

The concept of the MMA grew out of the desires of astronomers to investigate cold matter in the universe, the matter from which stars and galaxies form. The community definition of the MMA included both the ability to image interstellar molecular clouds with a resolution comparable to that that was achieved by infrared telescopes in studies of the same objects, and it included a desire to image protostars, protogalaxies, and starburst galaxies with enough sensitivity to detect these objects and with a resolution superior to that of the Hubble Space Telescope. That is, the MMA should be in all respects **the** telescope for the study of cold matter in the universe.

The result was that the MMA is the first synthesis telescope to be designed as a complete imaging instrument, capable of measuring all spatial frequency components of the sky brightness from zero to the longest array baseline. Astronomical images with the highest angular resolution, less than $0\overset{''}{.}07$, will come from the array in its largest configuration, and will be made using the Fourier synthesis algorithms that enable the array to simulate an aperture of 3 kilometers diameter. Low resolution images of large regions of the sky will come from a mosaicking mode, using the MMA in its most compact configuration much like a conventional single dish, the MMA antennas rapidly scanning the region to be imaged, in unison. These two capabilities have never been incorporated in a single instrument. The complexity of the sky at millimeter wavelengths and the unique interrelationship of astrophysical phenomena on a wide range of spatial scales that is characteristic of millimeter-wave scientific investigations make the melding of these capabilities a fundamental requirement for the MMA.

In specifying the scientific goals of the MMA, astronomers are calling for an unprecedented combination of sensitivity and angular resolution at short wavelengths, one that will make a wealth of unique astronomical opportunities and new science available for investigation. With the antennas spread over a 3 kilometer array, astronomers are able to observe in detail the formation of protostars and pre-planetary disks in molecular clouds. With the antennas clumped together in an area no more than 70 meters across, astronomers can observe the chemical evolution in molecular clouds which precedes, or perhaps initiates, star formation. Observations in widely separated frequency bands may be conducted simultaneously in support of studies of molecular excitation, with complete frequency coverage provided in all the atmospheric windows from 9 mm to 0.9 mm wavelength. With 40 antennas, the array is sufficiently fast, and the imaging characteristics of such high quality, that the astronomer will be able to see the results and modify the observing program as the observations are being made. The MMA is a unique and powerful instrument.

The burden of designing a powerful and unique instrument is that it requires an extension of existing technology. This is as true for the MMA – with its densely packed mosaicking configuration, broadband sensitive receivers, total power instrumentation, and precision antennas – as it was for the Keck Telescope with its segmented, optical quality primary mirror, and the GBT with its unblocked 100 meter aperture and real-time, laser-guided surface metrology. Application of significant technological advances is the *sine qua non* of the design of a forefront scientific instrument. Precise technical specifications of the Millimeter Array is the emphasis of the near-term planning for development of the MMA.

Millimeter Array Development Consortium

For several years we have developed the argument that a sensible way to fund the MMA was to begin with a design and development phase of three years, followed by six years of construction. The purpose of the design and development phase was to allow us to evaluate hardware options and to experiment with prototypes prior to committing to construction of multiples of 40 of each of the MMA instruments.

The utility of the MMA design and development phase has been additionally recognized as a means to address a number of technical issues (e.g., phase calibration) that the MMA concept either presents anew or carries to an extreme not previously experienced by existing instruments. Moreover, it is also possible to perform useful diagnostic work for the MMA problem areas with existing arrays. Given this, and the interest of our colleagues at the Owens Valley Radio Observatory (OVRO) and those affiliated with the Berkeley-Illinois-Maryland Association (BIMA), we began discussing a close collaboration between those of us at the NRAO working on the MMA and the university groups. The outcome of these discussions was formation of the MMA Development Consortium (MDC).

The MDC concept, while thought of originally in the context of a collaboration of the university groups in the early development stage of the MMA, has subsequently been broadened to include a longer term formal relation by which the California arrays serve a training function for students and postdoctorals, and they are used for MMA instrument prototyping in the operational phase of the MMA. It may also be possible and desirable for the two university arrays to be combined at a new, high elevation site in California so as to form a more powerful instrument. This may be particularly important if the MMA is built in the southern hemisphere.

The MDC has a steering committee of four members, two from the NRAO and one each from OVRO and BIMA, who define MMA development activities. Presently MDC working groups are being formed to evaluate the MMA development tasks. We believe the MDC concept is one that can be successful for the needs of the MMA and the university community, and that it could also benefit other large national projects where preservation of instrumentally related university groups was deemed important.

The MDC is organized such that it accomplishes its tasks by means of working groups composed of individuals at each of the three organizations. There are presently five working groups: antennas, receivers, phase calibration, software, and system. Substantial progress is being made in all areas.

MMA Advisory Committee

Definition of the MMA Development Consortium meant the MMA project needed a redefined advisory committee structure – the former advisory committee included members from OVRO and BIMA that should not, of course, be advising the MDC and hence themselves. The Advisory Committee was therefore reconstituted with members suggested by the MDC. The present membership is:

Fred C. Adams
University of Michigan

Thomas M. Bania
Boston University

John H. Bieging
University of Arizona

Edward B. Churchwell
University of Wisconsin

Neal Erickson
University of Massachusetts

Neal J. Evans
University of Texas

Paul Goldsmith
Cornell University

Richard Hills
Cavendish Laboratory

Gillian R. Knapp
Princeton University

Colin R. Masson
Center for Astrophysics

F. Peter Schloerb
University of Massachusetts

Philip Solomon
SUNY, Stony Brook

Jean Turner
University of California

Ewine van Dishoeck
University of Leiden

Robert W. Wilson
Smithsonian Astrophys. Obs.

Gareth Wynn-Williams
University of Hawaii

By the fall of 1995 so much progress had been made on the technical development of the MMA that the MAC recommended that a MMA Science and Technical Workshop be held to provide an opportunity for scientists to comment on design decisions and the priorities for scientific capabilities of the MMA. Below is the summary report of that workshop prepared by the MAC.

SUMMARY OF THE MMA SCIENCE WORKSHOP

On October 5-7, 1995, nearly 100 scientists and engineers gathered in Tucson for a workshop on the topic of the Millimeter Array (MMA). The twin objectives of the meeting were to update the scientific goals for the MMA and to compare those goals to the straw man design that had been developed by the technical working groups. To achieve the first goal, five scientific working groups and a technical group held separate meetings. To achieve the second goal, joint meetings were held. The scientific working groups summarized their conclusions in reports, which are appended to this document (not included in the LRP). Some of the most exciting scientific goals have been abstracted and listed as section 2 of this report [not included here]. Details may be found in the full report. Each report also contains recommendations on technical requirements pertinent to the goals of that group. Many of the technical requirements are a result of a very productive give-and-take between the scientific and technical working groups, which characterized the spirit of the workshop.

The Millimeter Array Advisory Committee (MAC) met at the conclusion of the meeting and agreed on a set of recommendations for the future development of the MMA. These recommendations were subsequently refined, based on the working group reports. The most salient recommendation of the MAC is that development of the MMA should proceed as soon as possible. The scientific case for the MMA, already strong when the proposal was written, has become much stronger. The pioneering work of the existing arrays has opened new areas for research that can only be properly developed with the MMA. The excellent atmospheric properties of the sites now under consideration and the advances in technology since the MMA proposal also led the MAC to recommend initial operation with a submillimeter band and outrigger stations to allow resolution significantly better than 0.1 arcseconds. The MAC also identified capabilities in the original proposal which are now of less importance.

The scientific goals summarized in section 2 [not included] demonstrate the broad scope of MMA science. From the largest structures in the Universe to the smallest, near-Earth objects, the MMA will revolutionize our understanding. The origin and evolution of galaxies, stars, and planetary systems will be studied by the MMA. The scientific and technological

foundations for the MMA are sound. We believe it is time to move forward with this revolutionary scientific instrument.

Site Studies

In recent years we have come to appreciate how important the MMA site is to the performance of the array. Specifically, for a user facility such as the MMA, the mean performance of the array is the important criterion, not the peak performance that transitory atmospheric conditions can allow. The MMA must be sited where the annual mean atmospheric transparency and stability are exceptionally good. For this reason we have focussed our site studies in the northern hemisphere on Mauna Kea, and in the southern hemisphere on northern Chile, both areas lacking pronounced seasonal variations. Presently we have a database of 26 months of atmospheric transparency data for Mauna Kea, and we are operating an interferometer to assess the phase stability. Similar equipment, a 225 GHz tipping radiometer and an interferometer to measure atmospheric phase, has been established at a site at 5000 meters (16,500 feet) elevation east of the village of San Pedro de Atacama in northern Chile. The Chilean testing equipment has been running for 13 months and show this site to be exceptionally good, competitive even with the South Pole for low values of precipitable water.

Figure III-1 is a panorama of the Chilean site. The area shown here is more than 5 kilometers in extent and the site continues to a still larger area beyond the limits of this photograph. The NRAO site testing equipment is located nearly at the center of the photo, too small to be seen from this perspective.

The atmospheric opacity measured by the 225 GHz tipping radiometer can be directly converted into a column density of atmospheric water. Having the water column, we can use standard atmospheric models to compute the atmospheric opacity as a function of frequency. Such a plot for a characteristic value of the atmospheric water on the Chilean site is shown in Figure III-2. Here we can see that on this site not only are the millimeter wavelength (frequencies less than 300 GHz) atmospheric windows transparent but so also are the submillimeter wavelength windows. These results suggested to the MAC and others that the MMA should have submillimeter capability as part of its initial receiver complement. The site is so good that the MMA should make full scientific use of it.

Fig. III-1. The potential MMA site in Northern Chile altiplano. The site elevation is 5000 meters (16,500 feet).

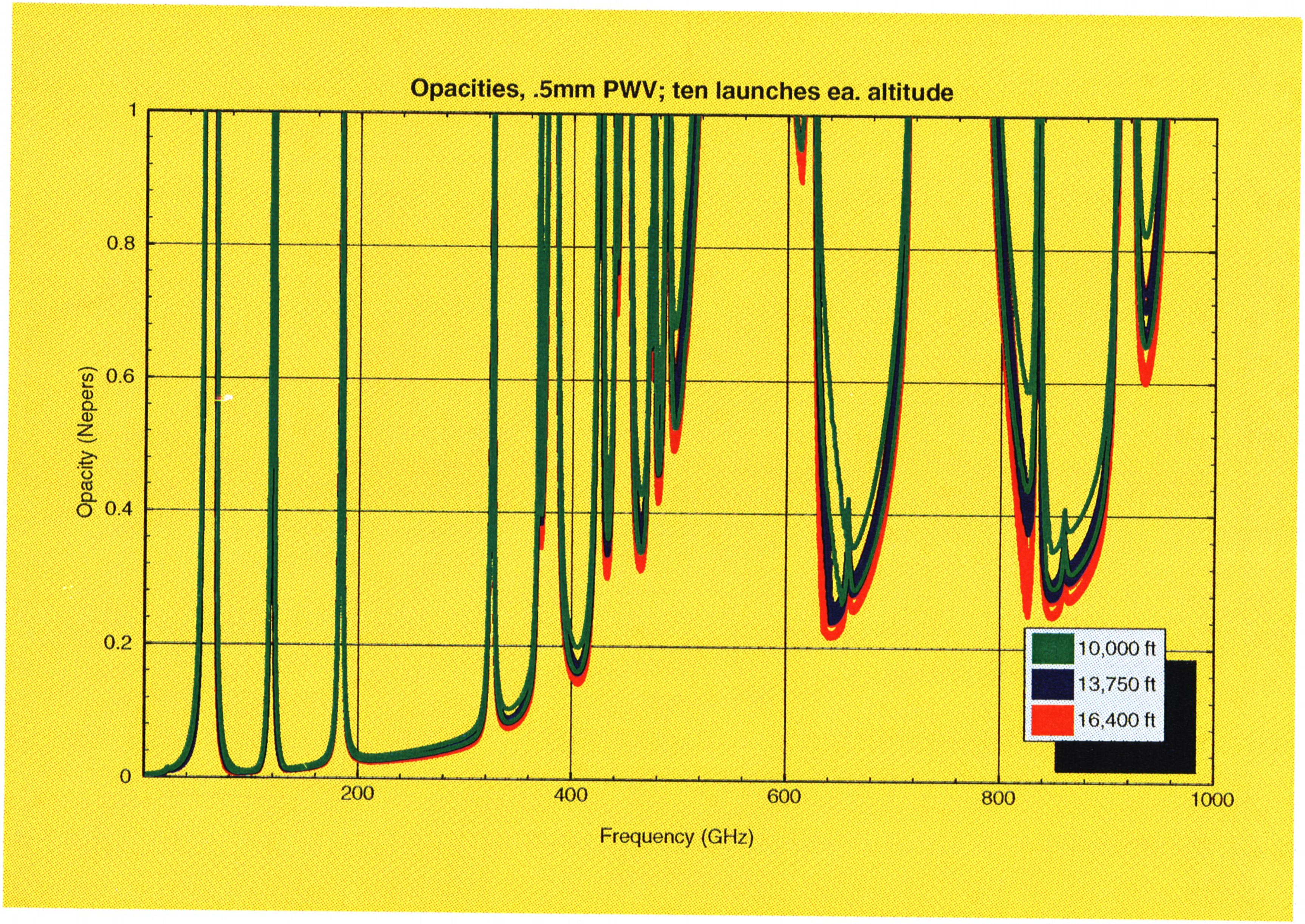


Fig. III-2. The opacity of the Earth's atmosphere as a function of frequency for a total water column above the site of 0.5 millimeter. The three curves show the effect of lower atmospheric pressure on the line wings at higher elevation sites for constant amount of precipitable water.

National and International Collaborations

The Atacama Array

The addition of a submillimeter receiving capability to the MMA makes the MMA project similar in scope to the array being planned in Japan by the Nobeyama Radio Observatory called the Large Millimeter and Submillimeter Array (LMSA). In principal, were the MMA and the LMSA to be located on the same site the two instruments could be used together for some class of scientific studies. The specific outlines of a MMA/LMSA collaboration have been discussed for three years in semi-annual meetings. The most attractive of several collaboration options is creation of the *Atacama Array* from the combined MMA and LMSA.

The premise of the Atacama Array is the location of both the MMA and the LMSA on a common site, but the arrays should be located approximately 10 km apart. Most of the year the two arrays operate independently in response to the demands of their respective communities. But for some period of the year (three months?) all the antennas of both arrays are moved out to stations around the locus of a circular or triangular pattern 10-15 km in diameter. This MMA + LSMA in a very large configuration is the Atacama Array. Observing time on the Atacama Array, and management of the operation, will be issues to be discussed in the next few years. Figure III-3 shows how the Atacama Array could be configured on the Chilean site under study for the MMA.

For a 12 km Atacama Array such as that given in Figure III-3 which operates at all the MMA and LMSA frequencies, the angular resolution varies over the range from 60 to 6 milli-arcseconds. The table below illustrates this and includes the corresponding linear resolution at the distance of some important astronomical sources.

Table 1. Atacama Array Resolution

		Linear Resolution At:				
Frequency	Angular Resolution	Ophiuchus	Sgr A	Magellanic Clouds	Cen A	QSO z ~ 1
90 GHz	60 mas	10 AU	520 AU	0.06 pc	1.5 pc	1. 5 kpc
230	20	3.4	170	0.02	0.5	0.5
345	15	2.6	130	0.015	0.4	0.4
650	8	1.4	70	0.008	0.2	0.2
850	6	1	50	0.006	0.15	0.15

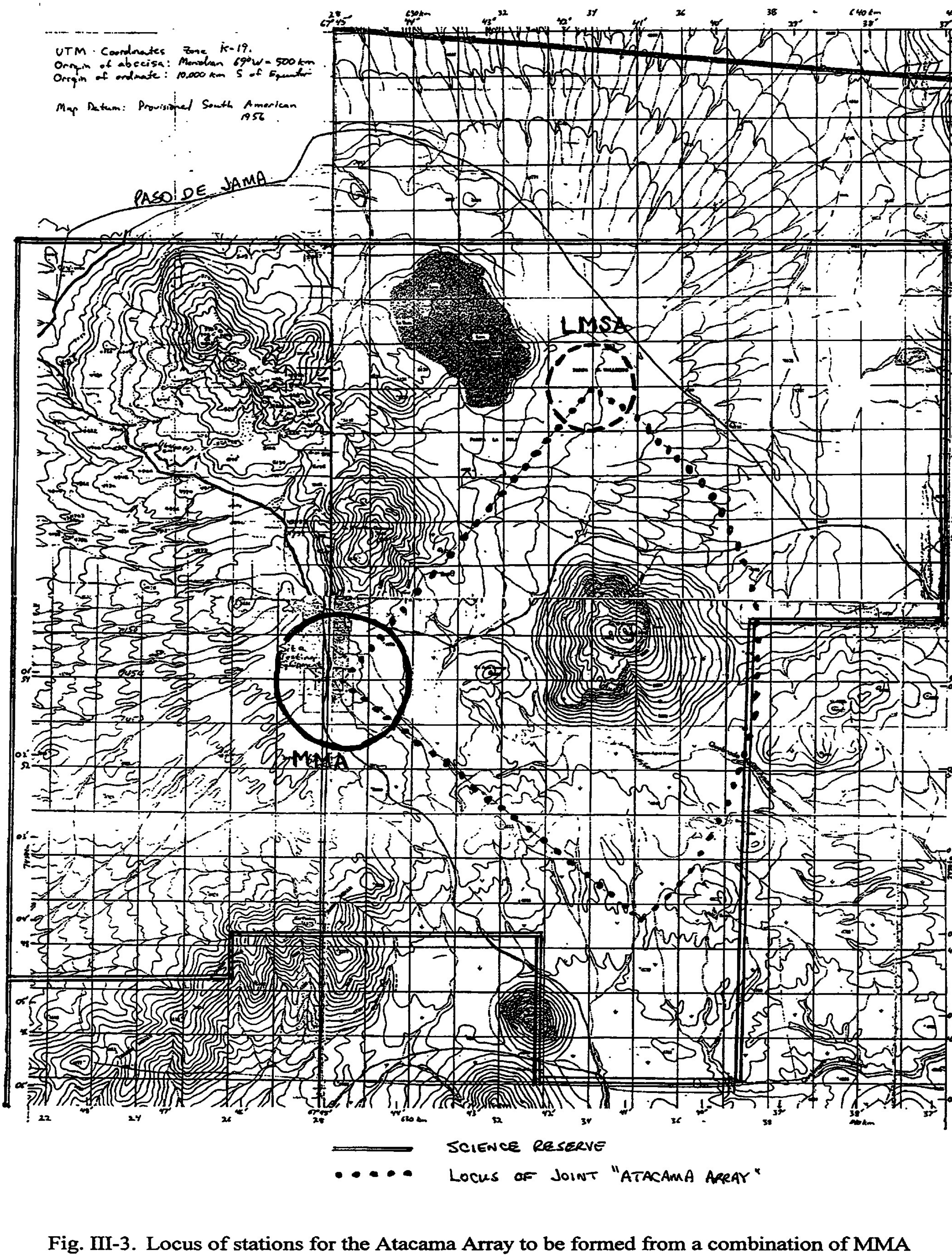


Fig. III-3. Locus of stations for the Atacama Array to be formed from a combination of MMA and LMSA antennas.

With a resolution of a few milli-arcseconds to a few tens of milli-arcseconds, the Atacama Array provides an imaging capability comparable with that of centimeter-wave VLBI instruments, but it does so as a connected phase-stable interferometer and it operates at wavelengths where thermal sources are bright. For thermal sources, the only instruments of comparable angular resolution are the optical interferometers, but these instruments give only visibility functions, not high-fidelity images.

Search for Neighboring Planetary Systems

A submillimeter capability for the MMA such as recommended by the MAC and long interferometer baselines (10 km) such as are found in the Atacama Array provide an opportunity for the MMA to participate in the NASA program being called *Exploration for Neighboring Planetary Systems*, or ExNPS. This program can provide a research partnership between the NSF and NASA.

At a wavelength of 350 microns and with baselines of 10 km, the MMA beam size is only 0".006. With a phase stable array, positional accuracies can be established to a precision equal to the synthesized beam divided by twice the signal-to-noise achieved on the source being observed. For the ExNPS program the plan is to observe hundreds or thousands of nearby stars and establish their positions relative to the system of background quasars. Repeated observations of these stars over months to years will allow astronomers to identify those stars with a proper motion that appears to be a response to the orbital motion of one or more planets. The capability of the MMA to identify such stars depends on the signal to noise at which the stars can be detected.

Figure III-4 is an illustration of the capability of the MMA operating at 850 GHz (350 microns) to detect the nearby stars in the Hipparcos catalog. Here we can see that with an integration time of 1000 seconds or less per star more than 35,000 stars are detectable; even with an integration time of 100 seconds or less 10,000 stars are detectable. The detectable stars themselves are spread all over the sky as shown in Figure III-5. This is a rich field of research ripe to be harvested by an agreeable NASA/NSF research partnership.

Long Range Plan

With approval of the NSF for funding of the MMA as one component of the NSF Major Research Equipment Program, we plan to complete the MMA design and development phase in three years, FY1998-2000. In the first year contract work on the first prototype antenna will begin; in the second year engineering tests of that antenna will be made and a second prototype will be built. At the end of the third year two of the MMA antennas will be built, equipped with

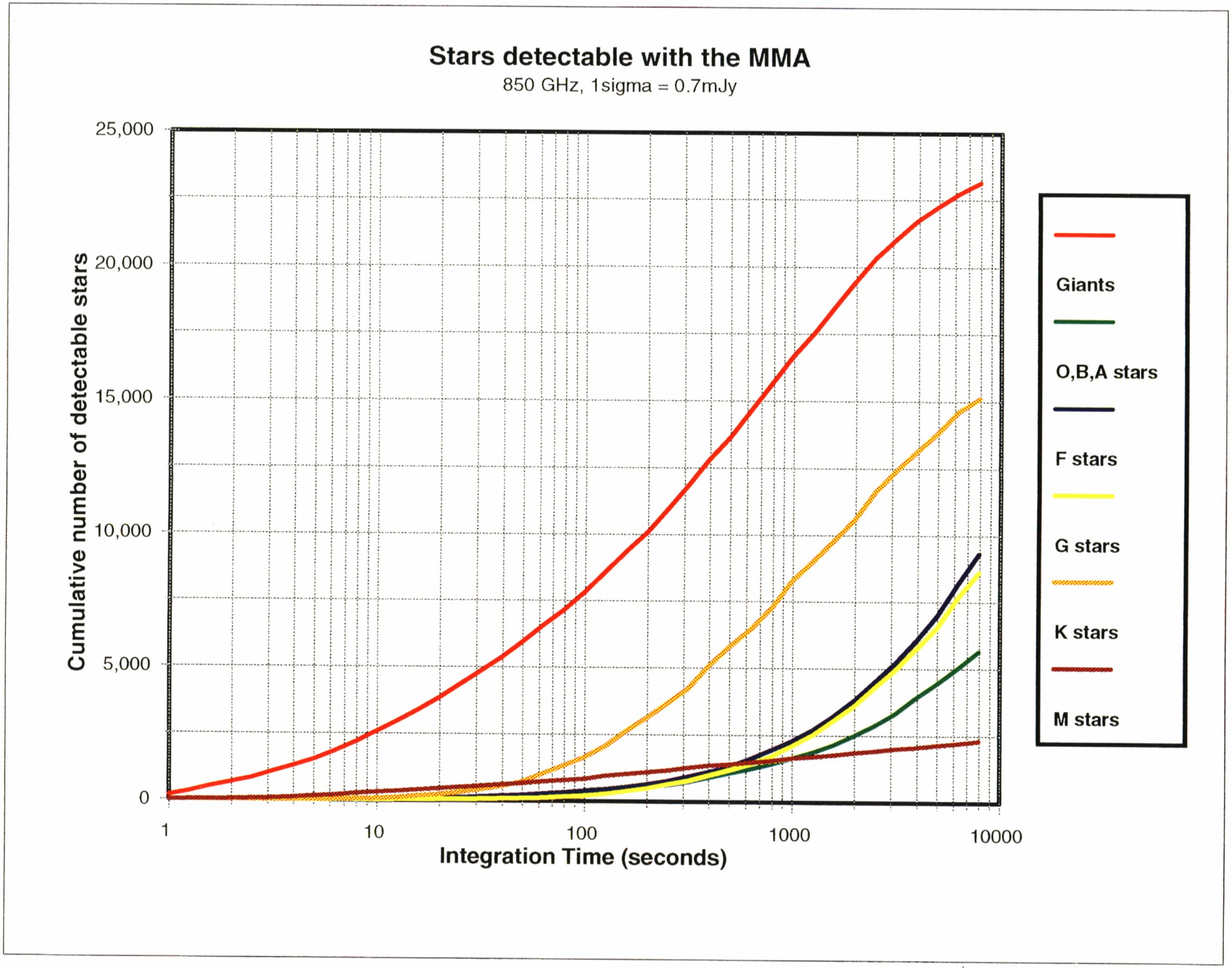


Fig. III-4. The cumulative number of stars in the Hipparcos catalog detectable by the MMA at 850 GHz in a minute of integration time.

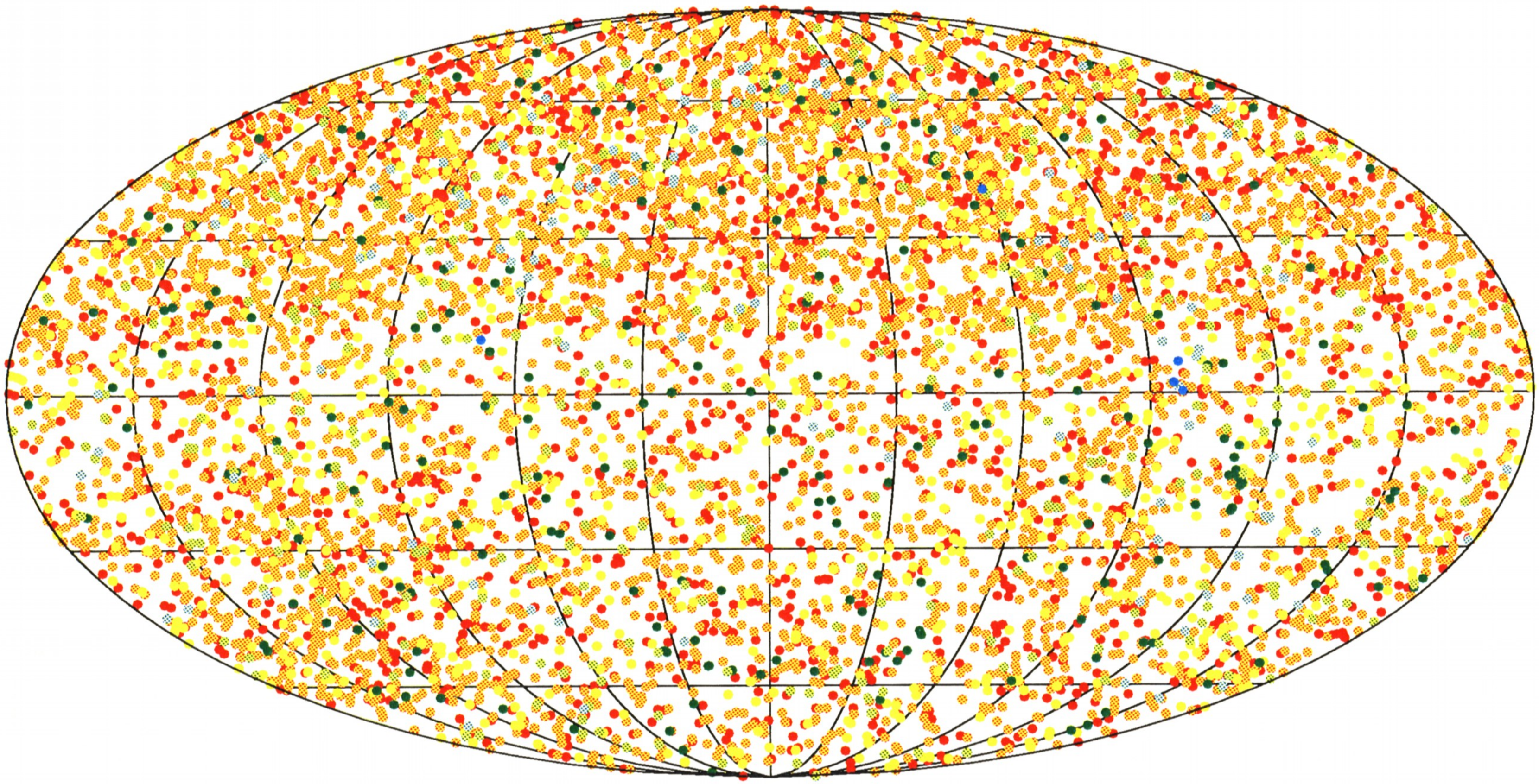


Fig. III-5. The distribution on the sky of the brightest 7700 stars at 850 GHz. For all these stars the MMA achieves a detection at 5 sigma or better in 5 minutes. The stars are color coded by spectral type.

MMA prototype electronics, and tested as an interferometer. The construction phase of the project will begin in FY1999, with the principal activity that year related to site and local infrastructure development. Cost and personnel figures for both phases of the MMA project are included in the table of Section VIII.

2. The 12 Meter Telescope

The NRAO provides state-of-the-art receivers at the 12 Meter Telescope for all atmospheric windows from 68 to 300 GHz. As new devices and technologies become available, existing receivers have been upgraded to provide the best possible performance. All receivers currently use SIS junctions, but we are watching closely the developments in HFET and monolithic microwave integrated circuit (MMIC) technology.

The new 8-beam, 1.3 mm SIS receiver system is now fully operational. This system provides a unique mapping capability that will be much in demand throughout the years of this long range plan. Construction continues on a new 8-receiver, 4-beam system for 3 mm. This will increase observing speed on point sources by a factor of nearly four, and on extended sources by a factor of nearly eight, compared with the existing dual-polarization, single beam system.

The 12 Meter Telescope is sensitive to molecular line emission from cold interstellar clouds, star forming regions, and aging stars. Such emission can indicate the mass present, its chemical composition, its temperature, and its kinematic properties. These quantities provide essential information on the basic life-cycle of a galaxy – gas to stars, then back to gas. The 12 Meter can study this emission not only in the nearby molecular clouds and stars of our own Galaxy, but also in some of the most distant known proto-galaxies in the Universe. In addition to spectral line emission from molecular clouds, the 12 Meter also observes cold dust from star forming regions and thermal continuum emission from distant quasars and active galactic nuclei.

Studies of the molecular content of galaxies will comprise a significant portion of the 12 Meter research effort in the coming years. Although progress towards the understanding of the process by which stars are formed in molecular clouds in the Milky Way is steady, the analysis is made difficult by the great complexity of the molecular radio emission arising because of the superposition of many clouds in a typical line of sight in the Galactic plane. More and more studies of the physical processes involved in star formation are exploiting observations of the distribution of molecules in galaxies. For the next few years there will be heavy demand on the 12 Meter Telescope to measure the general distribution of molecular gas, with emphasis on the relationship between the molecular gas and atomic hydrogen. Other studies will search for the densest clouds using molecular emission from molecules such as CS, HCO^+, and HCN. A promising approach is to study galaxies currently in the throes of an event, perhaps episodic, in which new stars are formed at a prodigious rate. The galaxies have been identified by their bright infrared emission, and the 12 Meter will be used to make an inventory of the molecular gas from which it is believed the new stars are forming. It is of interest as well to explore the possible reasons for the onset of this period of rapid formation of stars, and a number of avenues will be explored. For example, one theory postulates that star bursts are triggered by the merging of two galaxies, and observations will be made of the strength of the emission of CO as a function of the separation of galaxies in carefully selected pairs.

The 12 Meter has been a leader in the detection and study of high redshift line emission from galaxies, and significant effort will continue in this area. Studies of CO and CI are used to investigate the process of galaxy formation itself. So far, infrared-bright, molecular-rich objects have been seen at redshifts as large as $z = 2.9$. The objects thus far detected in CO will be examined for emission from other molecules and from atomic carbon, and searches will be made to find other forming galaxies.

The field of astrochemistry was pioneered with the 12 Meter (at that time the 36 Foot) Telescope and that area continues as one of the Observatory's most active and fruitful. The detection and study of interstellar and circumstellar molecules provides tests for theories of molecule formation and destruction and new diagnostic tools for the full spectrum of millimeter-wave astronomy. A promising new area of astrochemistry research at the 12 Meter Telescope is the study of refractory and metal-bearing molecules. Chemical models based on cosmic abundances suggest that numerous metal-bearing molecules should be present in detectable amounts in both the interstellar and circumstellar media. Yet, very few such compounds have been found so far. It is hypothesized that most of these molecules may have condensed onto dust grains, but a few refractory species, namely silicon compounds, are found in abundance in the gas phase. The whereabouts of gas phase, metal-bearing molecules is one of the outstanding mysteries of astrochemistry.

One of the most active areas of research at the 12 Meter in the coming years will be wide-field, rapid imaging of both continuum and spectral line sources. New techniques and instruments will facilitate such research. Specifically, the on-the-fly observing mode is available both for continuum and spectral line observations, for single-beam and for multi-beam systems. In this mode, data are taken continuously while the telescope is scanned across a source, which is a much more efficient mapping mode than the traditional step and integrate technique. This new method has been used for observations of many sources, two of which are shown on the accompanying figures (Figures III-6, 7, and 8). Figure III-6 is a combined image of the 1.6 GHz

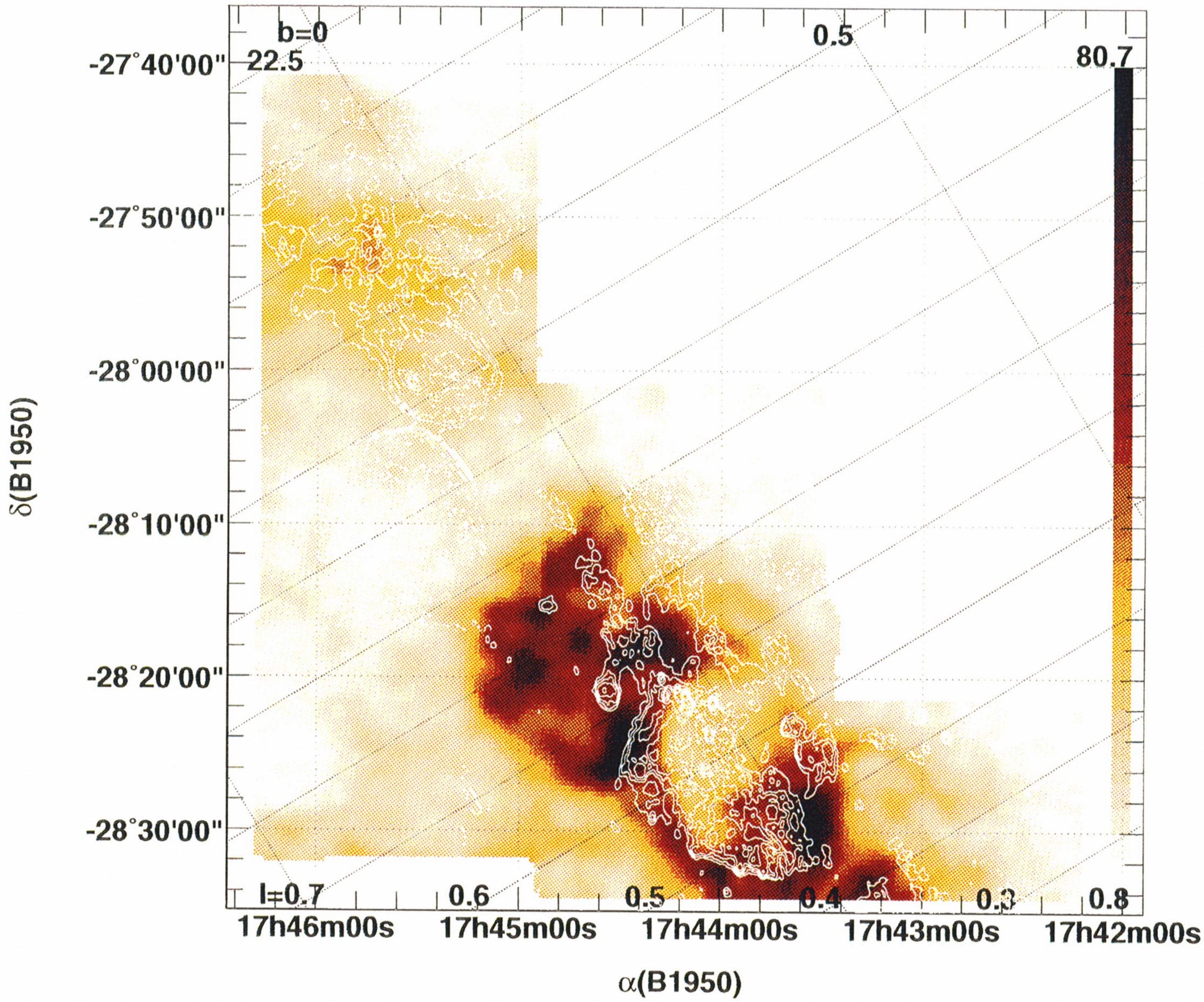


Fig. III-6. An overlay of 18 cm radio continuum emission measured by the VLA (contours) and the $^{13}CO(1\text{-}0)$ line emission toward Sgr-B2 mapped in on-the-fly mode at the 12 Meter Telescope. The distribution of CO at a velocity of 22.5 km s^{-1} is shown.

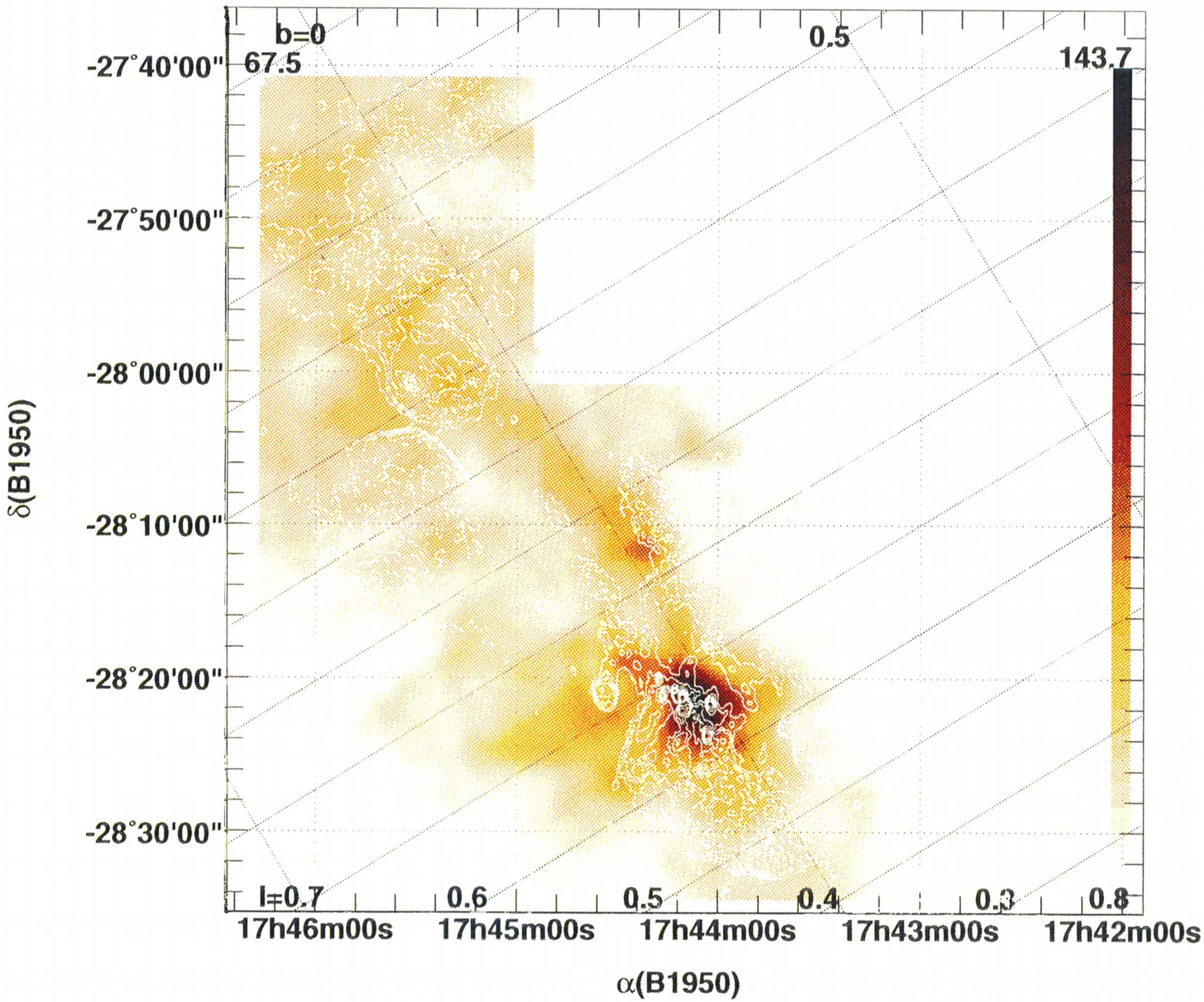


Fig. III-7. As above, at a CO velocity of 67.5 km s^{-1}.

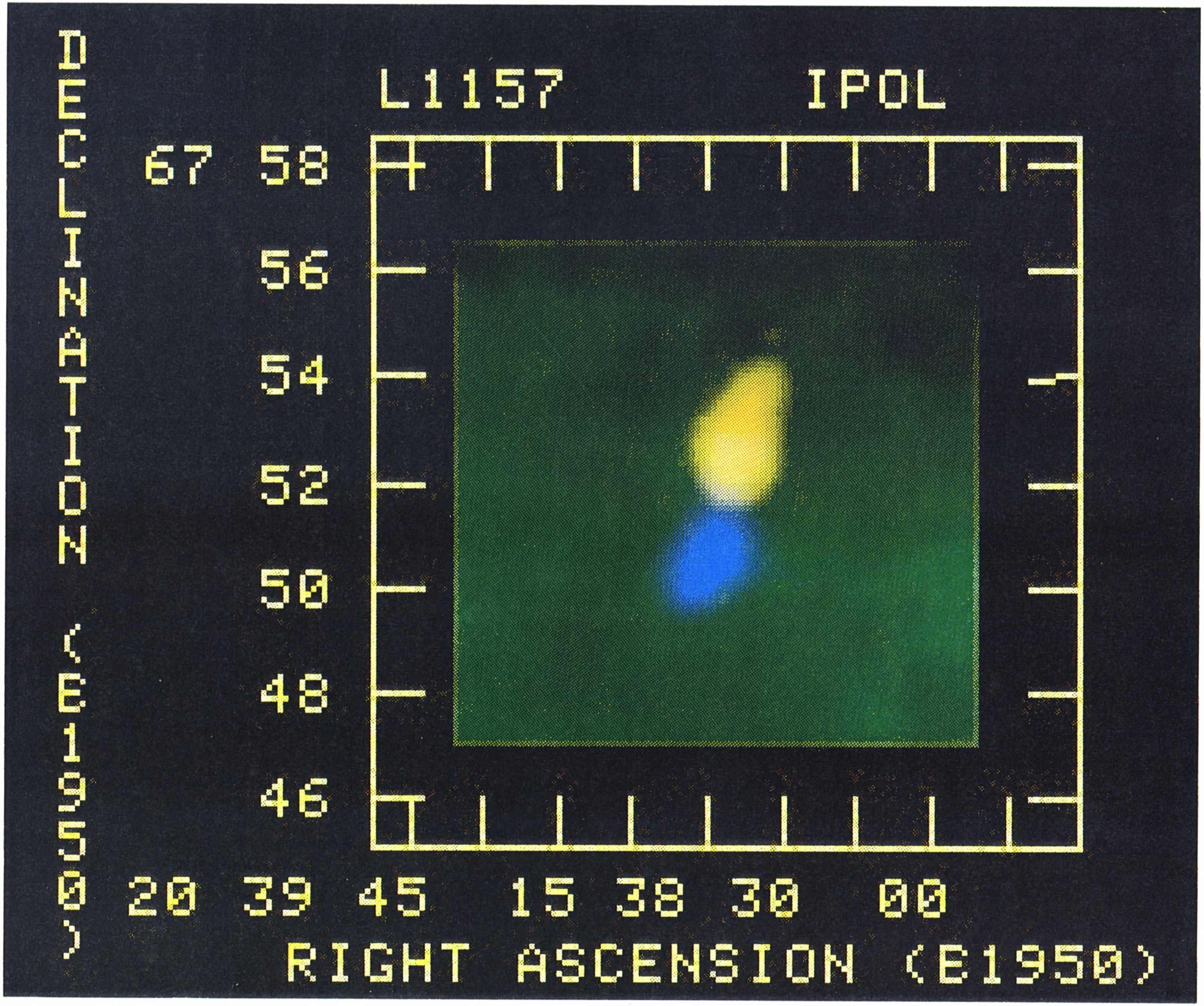


Fig. III-8. CO emission toward a protostar in the dark molecular cloud L1157. The CO is expelled by radiation pressure from the first light of the newly formed star.

continuum emission from the vicinity of the HII region Sgr-B2 as seen by the VLA (contours) and the $^{13}CO(1\text{-}0)$ emission at a velocity of +22.5 km s^{-1} (shown in color). Notice that the CO at this velocity exists only on the periphery of the HII region as if the molecular gas forms a shell encompassing the ionized gas. Such a model is confirmed by the CO image at a higher velocity, +67.5 km s^{-1}, which is shown as Figure III-7. At this higher velocity we are seeing only the gas moving along our line of sight at the most extreme redshift. For a spherical molecular shell that is expanding or contracting, this material is in a *cap* along the line of sight to the kinematic centroid; this is indeed what we see. Observations such as this provide the scientific insight sought by astronomers.

Figure III-8 is another example of an on-the-fly observation; this time it is an observation of a nearby star still in its formation process. Again, this is a map of CO emission. The gas shown in yellow is material flowing outward from the protostar in a direction away from us; the gas colored in blue is moving toward us. The gas motion is driven by the radiation pressure of the first light from the protostar and the conical shape of the emission is a result of a dense circumferential disk surrounding the star that collimates the outflow and prevents the outflow from being isotropic and spherical. By computing the pressure in the observable outflowing gas, astronomers can compute the size and confining pressure of the invisible circumferential disk.

The on-the-fly technique is currently the primary observing mode for the 8-beam receiver, and will probably become the main observing mode for the 8-receiver, 4-beam, 3 mm system currently under construction. An example of an 8-beam image is shown in Figure III-9. This 4-channel mosaic of the Orion A molecular cloud shows many of the well-known spatial features of this region, such as the bar, hot core, and northern cloud, along with several previously unnoticed features on the northwest and northeast parts of the image. Approximately 1.75 hours of telescope time was required to obtain this image, which has a single-channel rms noise of ~0.35 K.

Finally, a real-time link now exists between the 12 Meter Telescope and the Kitt Peak VLBA antenna. The link allows the 12 Meter to receive the maser local oscillator signal from the VLBA control room, and allows the 12 Meter to transmit an IF signal back to the VLBA tape recorder. This link greatly reduces the work involved in configuring the 12 Meter for millimeter wavelength VLBI observations. Routinely scheduled VLBI sessions now take place.

Future Plans

In the period of the long range plan, the 12 Meter Telescope and the Tucson staff will play a growing role in the development of the Millimeter Array. As the MMA project develops, there

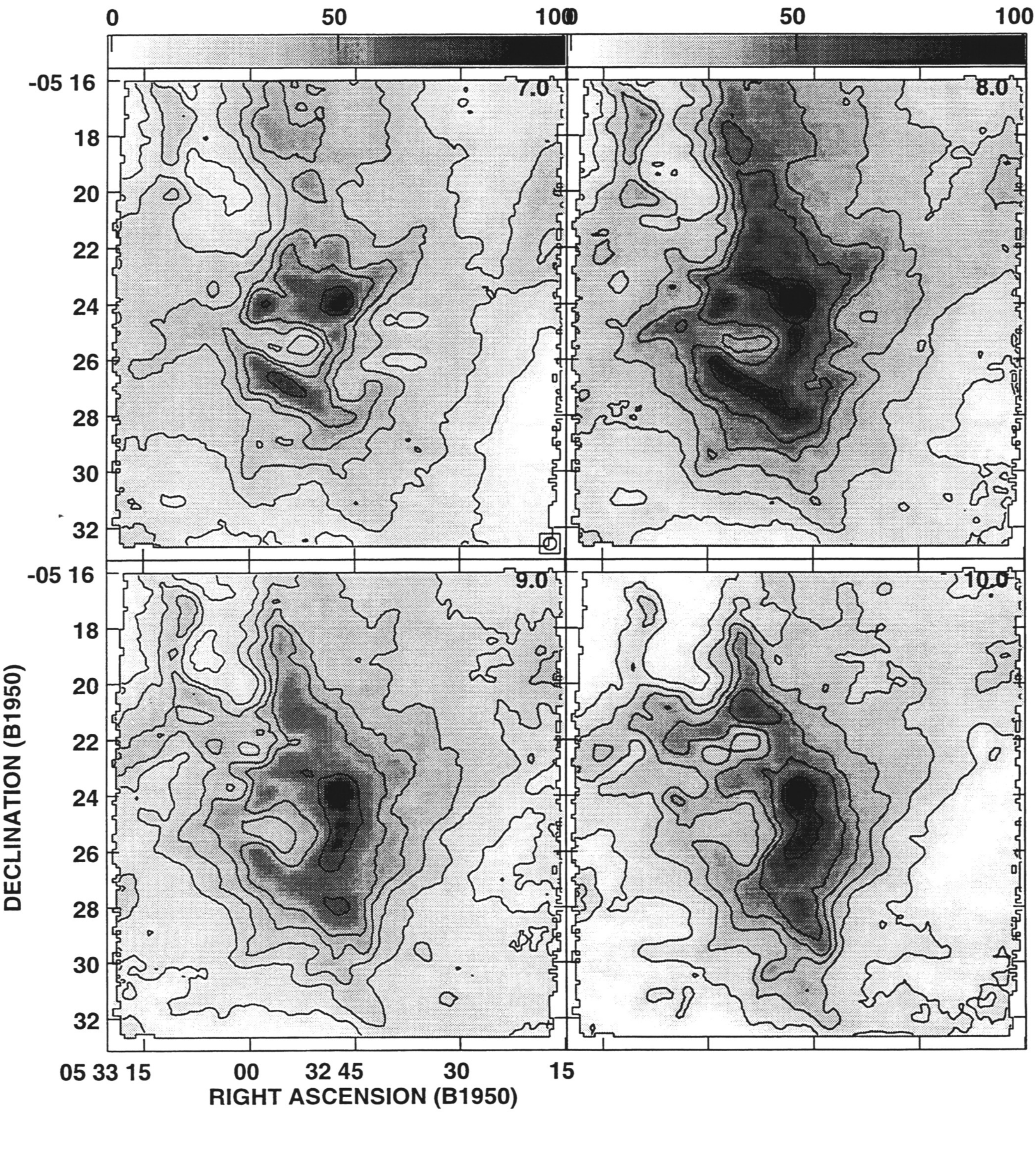


Fig. III-9. A map of the CO(2-1) emission in the Orion cloud made with the 8-beam SIS receiver in on-the-fly mode. The CO velocity is indicated in each panel.

will be the necessity for real hardware design, prototyping, and testing, including multi-band, millimeter, and submillimeter-wave receivers, digital spectrometers, and continuum backends. The 12 Meter Telescope will serve as a testbed for these developments, and the prototype MMA instrumentation will be used by visiting observers as one important step in the evaluation process.

Specific instrumentation plans for development of MMA hardware include the following:

- Evaluation of the prospects and penalties of a high frequency IF on the performance of SIS receivers;
- Assessment of the practical utility of MMIC devices as a LO source at frequencies at and below 115 GHz;
- Design and prototype of a phase-locked laser local oscillator system;
- Experimentation with a wideband HFET as a fundamental amplifier at 3 mm wavelength for continuum observations;
- Design of a wideband digital autocorrelator for use with multi-beam receivers.

IV. VERY LONG BASELINE ARRAY

Status

The VLBA is now operational in all its major observing modes. It is routinely scheduled in response to observing requests that are received at three proposal deadlines annually (1 February, 1 June, 1 October). The VLBA supports Global VLBI Network sessions interspersed during the year among the scheduled VLBA-alone observing.

Among the principal reasons the VLBA was built was to provide high fidelity imaging on milli-arcsecond angular scales. Prior to the VLBA the *ad hoc* arrays of existing radio astronomical antennas involved in VLBI observations were so heterogeneous in their instrumentation that the astronomer's ability to produce a reliable image was limited by things such as mis-matched IF filters from one antenna to another. The VLBA designed these problems out of the system by constructing an entire system of identical receivers and antennas. That was the theory and that now is the reality.

Figure IV-1 is a recent VLBA image of the active galaxy NGC 1275 (3C 84) made at a frequency of 15 GHz. The entire extent of the nuclear region of the galaxy shown here is less than 0."02, and the image detail within this incredibly small angle is unprecedented in astronomy. With VLBA images such as this we can explore the physics of active galactic nuclei – physics that we presume is a manifestation of a massive black hole – at a level of precision that is demanded by the physical scale of the phenomenon. Moreover, by observing galaxies such as this on approximately yearly intervals, we expect to be able to watch the evolution of the source physics and infer not only the nature of the central object but also we will be able to establish the pressure and kinematics of the gaseous medium in which the black hole is embedded.

For galaxies at cosmological distances, the size scales of the nuclear radio sources are one to a few parsecs; even for radio emitting material expelled from those nuclei with relativistic velocities the corresponding time scales for change are one to a few years. Hence, VLBA observations repeated annually are sufficient to allow us to follow source changes. On the other hand, for some highly luminous objects such as supernovae the characteristic size scale is far smaller and the corresponding time scale for change so brief that they could not be studied prior to the existence of a dedicated VLBI instrument such as the VLBA. Figure IV-2 shows such an example. It is a series of VLBA images of the radio emission from the supernova 1993J in the nearby galaxy M81. These VLBA observations were made over the course of a year following the supernova outburst, and they illustrate one of the operational strengths of the VLBA and

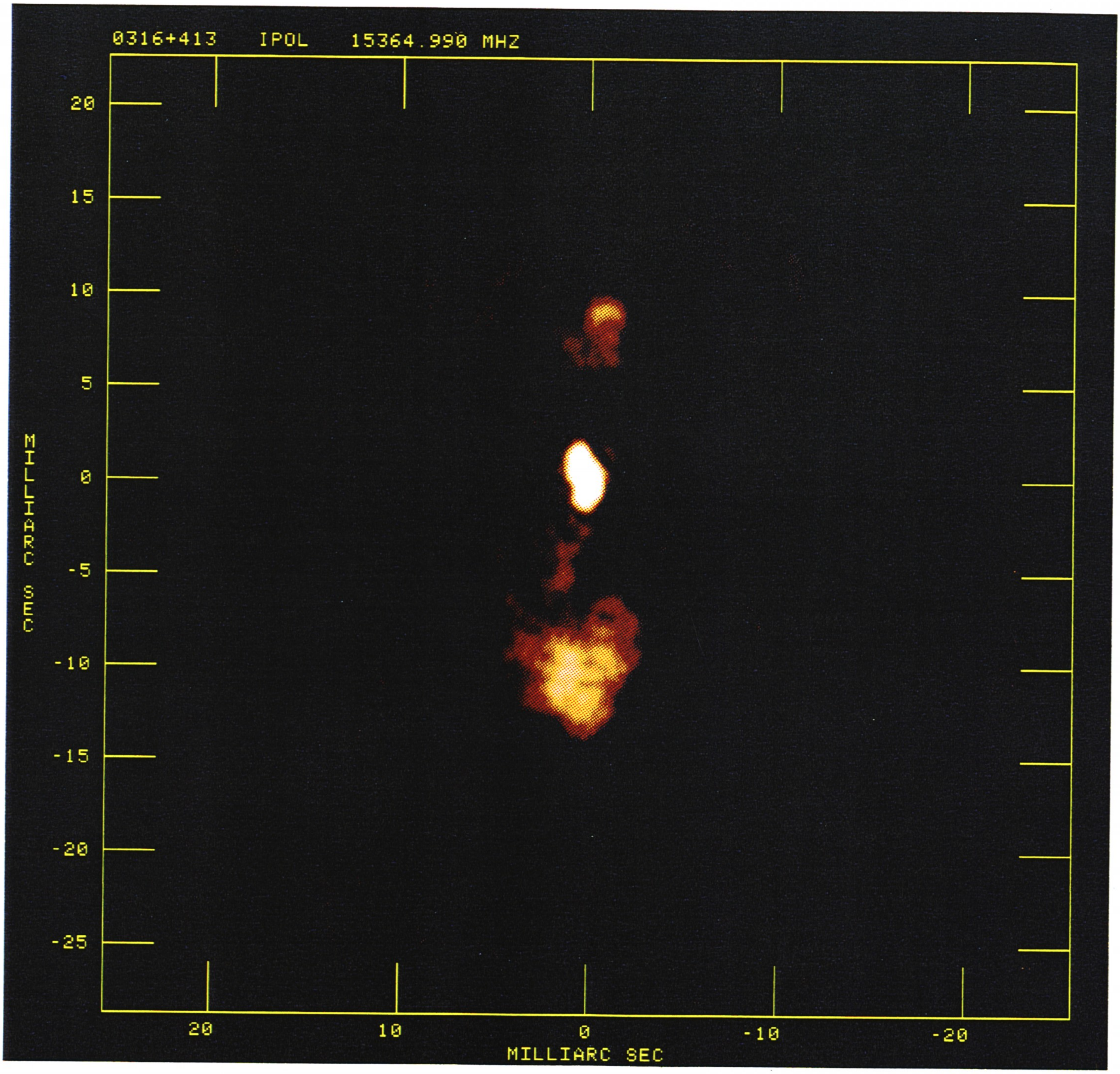


Fig. IV-1. A VLBA image of NGC 1275.

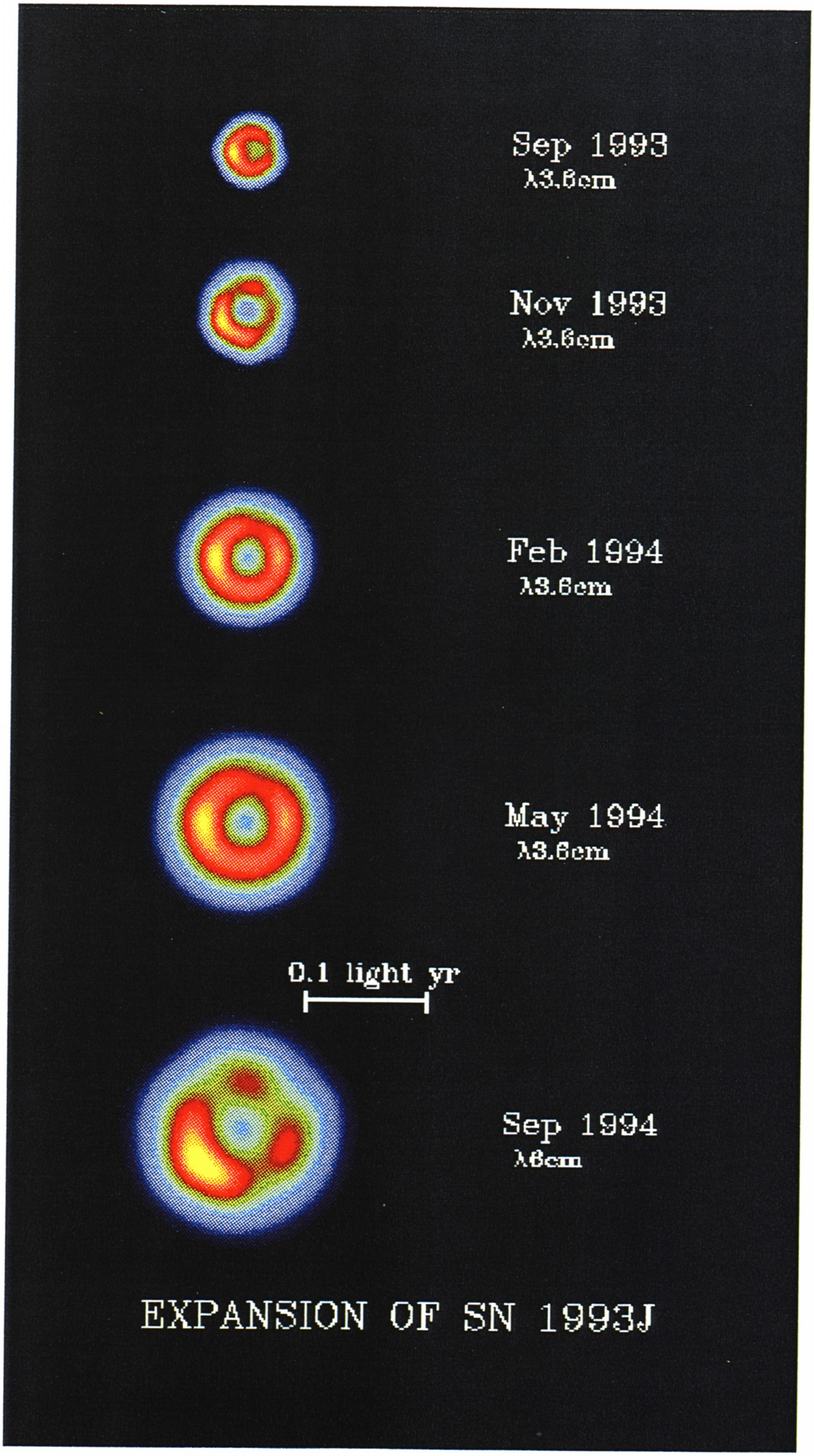


Fig. IV-2. Multiple epoch VLBA images of the supernova 1993J in the nearby galaxy M81.

indeed also of radio astronomy. The VLBA was able to follow the expansion of the supernova remnant with enough resolution to see the formation and evolution of the supernova shell in the first year after outburst and it was able to go throughout that year – no time was lost for the six months M81 was a daytime object.

For objects still closer to us, such as stars in the Milky Way, the angular resolution of the VLBA corresponds to astronomical-unit length scales. Figures IV-3 and IV-4 illustrate the ability of such incredibly high resolution for explorations of stellar physics. These two figures are VLBA spectral images of SiO emission from the AGB star TX Cam. The first figure shows the distribution of SiO masers in the stellar atmosphere. Here we see that the SiO forms at approximately twice the stellar diameter where the atmosphere has cooled sufficiently for refractory molecules to form and be stable. Repeated observations show these masers to change position as the clumps of gas aggregate and disperse. Spectral polarimetry of the SiO maser spots allows us to map the magnetic field in the stellar atmosphere. This is shown on Figure IV-4. this is a VLBA image of the electric vectors obtained from full Stokes parameter imaging of TX Cam. The tangential distribution of electric vectors indicates that the magnetic field is principally radial and that the field is dragged out from the star with the stellar wind. Detailed information such as this mapped across a stellar disk with a resolution of a small fraction of the stellar radius comes uniquely from the VLBA.

Present Instrumentation

The VLBA is a dedicated instrument for very long baseline interferometry. The ten antennas are distributed about the United States in a configuration designed to optimize the distribution of baseline lengths and orientations (u-v coverage). Baselines between 200 and 8000 km are covered, which provides resolutions up to 0.2 milli-arcsecond at 43 GHz. The shorter baselines, and hence the highest concentration of antennas, are near the VLA for optimal joint observations and to allow for a future project to fill the gap in the range of baselines covered by the two instruments. The antennas are 25 meters in diameter and of an advanced design that allows good performance at 43 GHz and useful performance at 86 GHz. The antennas are designed for remote operation from the Array Operations Center (AOC) in Socorro. Local intervention is only required for changing tapes, for maintenance, and for fixing problems.

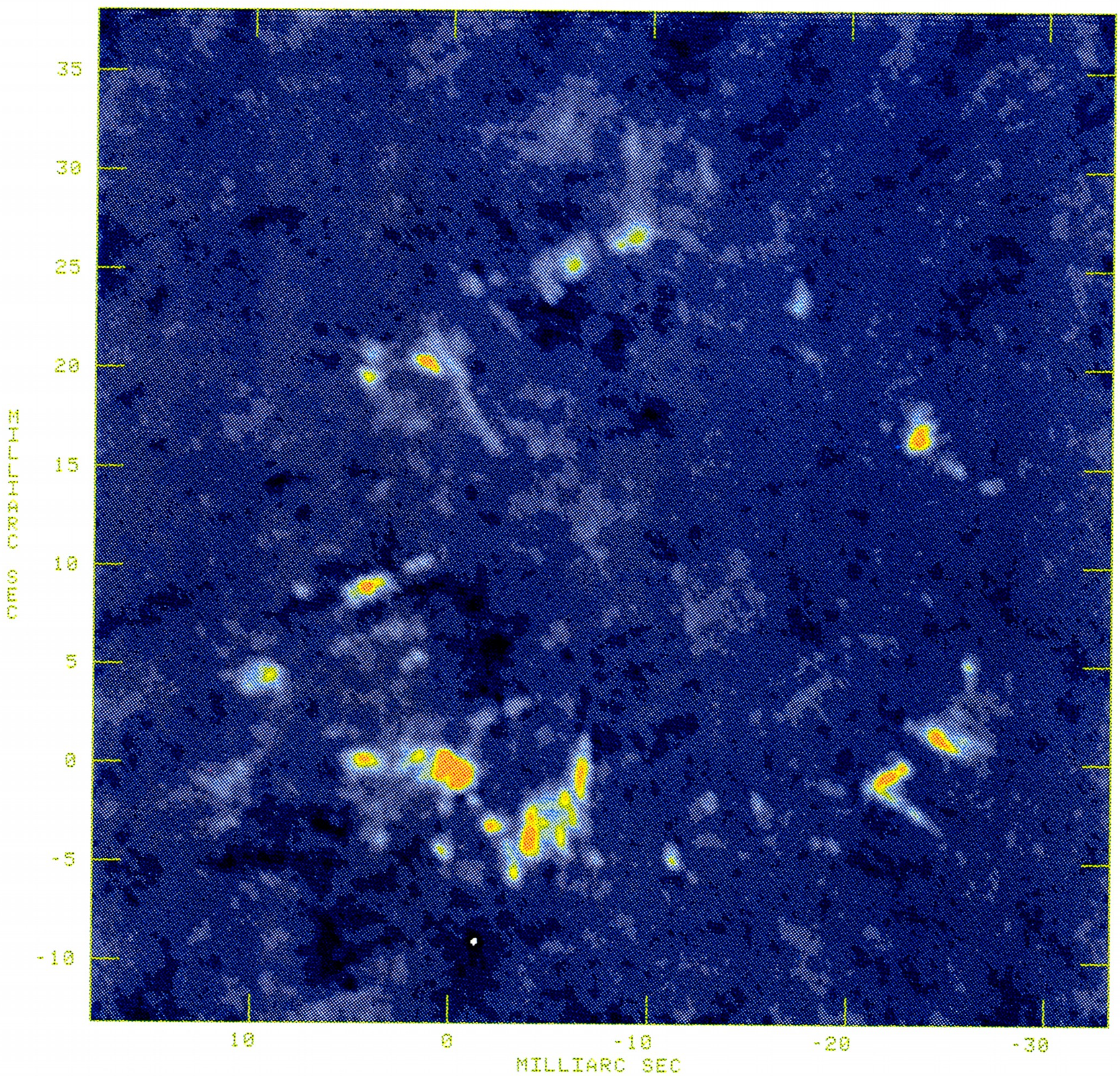


Fig. IV-3. A VLBA image of the SiO maser emission in the extended atmosphere of the star TX Cam.

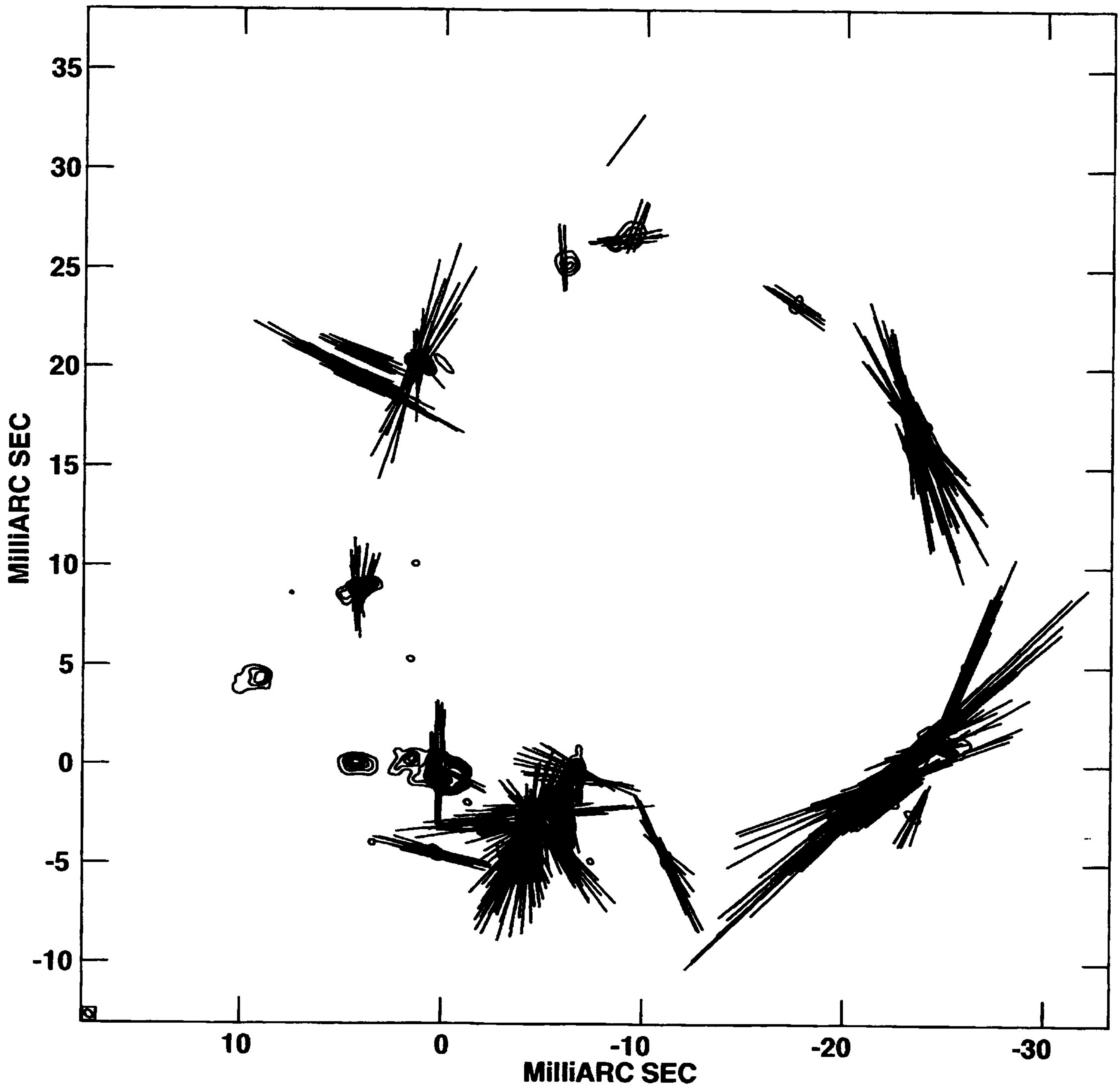


Fig. IV.4. The electric vectors of the polarized SiO emission in the atmosphere of Tx Cam.

Table IV-1. VLBA Receiving Systems

Band Designation (Note 1)			Frequency Range (GHz)			Aperture Efficiency (Note 2)	System Temp [K] (Note 3)
330	90	P	0.312	-	0.342	0.45	195
610	50	P	0.580	-	0.640	0.40	200
1.5	20	L	1.35	-	1.75	0.57	32
2.3	13	S	2.15	-	2.35	0.50	34
4.8	6	C	4.6	-	5.1	0.72	40
8.4	4	X	8.0	-	8.8	0.70	35
14	2	U	12.0	-	15.4	0.50	73
23	1	K	21.7	-	24.1	0.60	100
43	0.7	Q	41.0	-	45.0	0.45	100

Notes:
1. Megahertz/gigahertz frequency; centimeter wavelength; conventional radio (or VLA) letter codes.
2. Overall aperture efficiency and total system noise temperature at zenith. Values are representative of those measured on several VLBA antennas.
3. Single-frequency performance (without dichroic) shown.

The VLBA is outfitted for observations in nine frequency bands as shown in Table IV-1. All receivers are dual polarization. The receivers at 1.4 GHz and above contain cooled HFET amplifiers from the CDL. The low-frequency receiver is a room temperature GaAsFET. The cooled receiver for each band is in a separate dewar mounted directly on the feed to minimize noise contributions from waveguides, etc. All receivers cover both right and left circular polarization. The VLBA requires highly accurate frequency standards and a wide-bandwidth recording system at each site. The VLBA sites use a hydrogen maser manufactured by Sigma Tau Corporation for the frequency standard. The recording system is based on a Metrum (formerly Honeywell) longitudinal instrumentation tape recorder that has been extensively modified by the Haystack Observatory. The recorder is similar to the one used in the Mark III and future Mark

IV VLBI systems. There are two drives at each VLBA station to allow more than 20 hours of recording at 128 Mbits/second between required visits to the station for tape changes. The tapes are 16 microns thick, with about 3.4 miles of tape on a 14-inch reel.

The VLBA correlator is located at the AOC in Socorro. It is able to correlate as many as eight input data channels from each of up to twenty sites. For most modes, 1024 spectral channels can be provided for each input channel. The correlator is of a novel design, pioneered by the Nobeyama Radio Observatory in Japan, in which each bit stream is Fourier transformed to a spectrum before cross correlation (the *FX* architecture). Output data is archived on DAT tapes, while the input tapes are recycled for more observing shortly after correlation. Users receive their correlated data in FITS format on any of several media, including DAT and EXABYTE tapes.

VLBA postprocessing is done in the astronomical image processing system (AIPS). Software development for VLBI in AIPS is essentially complete apart from support for some advanced capabilities of the array such as polarization calibration, utilization of the pulse calibration system and Space VLBI. Astrometric/geodetic processing will be done primarily in the system developed by the Crustal Dynamics Project, now Dynamics of Solid Earth (DOSE), at NASA. Over the next few years, the postprocessing will shift to the AIPS++ system as that system acquires the necessary capabilities. The in-house computing for the VLBA is done mainly on workstations of the SUN IPX and IBM RS/6000-560 and RS/6000-580 classes.

Future Plans

For the immediate future, much of the available effort will be focused on obtaining the full potential efficiency of the correlator and improving the antenna performance. The VLBA correlator, when fully operational in all its modes, will be capable of correlating data from the 10-element VLBA at four times faster than real time (a factor of two from the number of correlator inputs available compared to the number of VLBA stations, and another factor of two by replaying the tapes at twice the recording speed). Attaining this level of efficiency will require fine-scale debugging of the correlator real-time software and streamlining of correlator operations. Most major modes of the correlator are now supported by the software, they have been tested, and they are being used in science observations.

In the longer term, over the period of this long range plan, emphasis will be given to improving our knowledge of the array geometry, to enhancements in high frequency observing capabilities and in handling Space VLBI data from the VSOP mission.

The performance of the VLBA as a geodetic/astrometric instrument will be tested and improved as the geodesy community works toward their goal of station motion measurements accurate to 1 mm per year. Most of these projects will not involve significant funding. Some hardware may be needed; for example, tilt meters may be needed on the antennas to improve pointing.

A vital continuing project is to make the VLBA phase stable. With a connected element array such as the VLA, the phase of the array elements is found by observations of phase-calibration sources of known structure. This allows images to be made without using the self-calibration techniques upon which VLBI normally depends. Weak sources, which require coherent integrations over the whole time of an experiment and over all baselines, can thus be observed, and imaging of complex sources is simplified. Accurate relative positions can be measured which allows for proper motion and parallax studies and for alignment of images made at different frequencies or different times. If phase calibration using nearby calibrators can be used on the VLBA, it will have a major impact on the science that can be done. The success of phase-calibration for the VLBA will depend critically upon the accuracy of the geometric model for the array, the earth, and the celestial sources. A simple geometric model can be used to extend the phase-coherence time from tens of minutes up to several hours. Recently we achieved full phase coherence by using a more complete and accurate geometric model based upon extensive geodetic and astrometric observations, and the task now is to make this capability a routine function for VLBA users.

One of the major advantages of the VLBA over the older VLBI Networks is its ability to work at high frequencies. The antennas were designed for good performance at 43 GHz, and receivers for that frequency have been installed and are working well. The antenna structures were designed to work to 86 GHz, and the surfaces were figured as well as possible, within the technologies used, to permit observations at this frequency. Present measurements gave an efficiency near 40 percent at 86 GHz, which is adequate. We plan to install two 86 GHz receivers in the last quarter of 1996, thereafter adding two per year. The completion of this project will double the maximum angular-resolution of the instrument and make the VLBA the instrument of choice for high-resolution observations at the longer millimeter wavelengths.

A number of other technical developments are scheduled for the period of this long range plan. For sensitivity-limited observations, the instantaneous recording rate of the VLBA can be doubled for a short period of time by recording simultaneously on both tape drives. This will be accomplished by means of an enhancement to the correlator software. Both these developments will involve substantial testing before they can be made available for routine observations.

Scheduling and Observing

Astronomical observing on the VLBA consists of Global Network projects during the Network sessions and VLBA projects at other times. Global Network observing amounts to about three weeks every three months and is expected to continue into the future. Projects that need more baselines than the VLBA can provide, or that need to use large antennas for sensitivity, will continue to use the Network. Most Network projects use the VLBA, the 140 Foot Telescope, the VLA, and antennas of the European VLBI Network (EVN). Arecibo, NASA's Deep Space Network, and antennas in places such as South Africa, Brazil, Japan, Australia, and China are occasionally used. NRAO, along with the EVN, administers the proposal submission and, along with the Europeans, assesses the Network projects, thus allowing a uniformity with VLA and VLBA projects.

V. VERY LARGE ARRAY: UPGRADE PROJECT

1. VLA Science

The design definition for the VLA was a capability to provide radio images at the same angular resolution as was achievable with large ground-based optical telescopes. This definition came from the scientific need to compare images from the two telescopes in order to extract the astrophysical insight the two would offer. If the resolutions are too disparate, the scientific ambiguities are so great as to render the comparison meaningless. Since the seeing-limited resolution of optical telescopes is of order one arcsecond, and since the workhorse wavelength of the VLA was thought of as 13 cm, these two considerations implied a maximum dimension for the VLA of 27 km. The VLA does in fact achieve the design resolution, and its images are routinely used together with optical images in scientific investigations of a wide range of astronomical sources. One such example is shown in Figure V-1; it is an overlay of an optical image of the nearby galaxy M33 with a VLA image of the HI in this galaxy. Notice that the extent of the HI is nearly twice that of the starlight and that the gas distribution is highly patchy. Both the relation of the gas distribution to the stellar distribution and the gas morphology tell us about the evolution of stellar formation and evolution in M33 – of course, we need both the radio and optical images for such a study.

Another galaxy that has been attracting much attention recently is NGC 4258. VLBA observations in 1995 demonstrated convincingly that a supermassive black hole, a black hole of 36 million solar masses, exists in the nucleus of this galaxy. Optically the galaxy appears to be a normal disk galaxy. But at radio wavelengths it is very distributed; the VLA image is shown in Figure V-2. It appears as if the radio *arms* of the galaxy sweep back and forth across the sky. Is this effect, seen uniquely at radio wavelengths, a manifestation of the nuclear blackhole?

Surprises are found by the VLA in the Milky Way as well. Figure V-3 is a VLA image of the star forming region W49. The brightest emission in this region, which is wholly obscured at visible wavelengths, comes from the ionized gas of newly formed massive stars. The arc-like spatial distribution of these stars suggests that they were formed contemporarily as a result of a common triggering phenomenon. One can use images such as this to address the most fundamental astrophysical questions.

Even closer to home the VLA contributes to our understanding of the complex processes on the sun. Figures V-4 and V-5 are VLA images of the sun. The first is a montage showing the x-ray emission from the active sun together with the VLA images of part of the solar disk made simultaneously with the x-ray image. The structure in the VLA image outlines the boundaries of

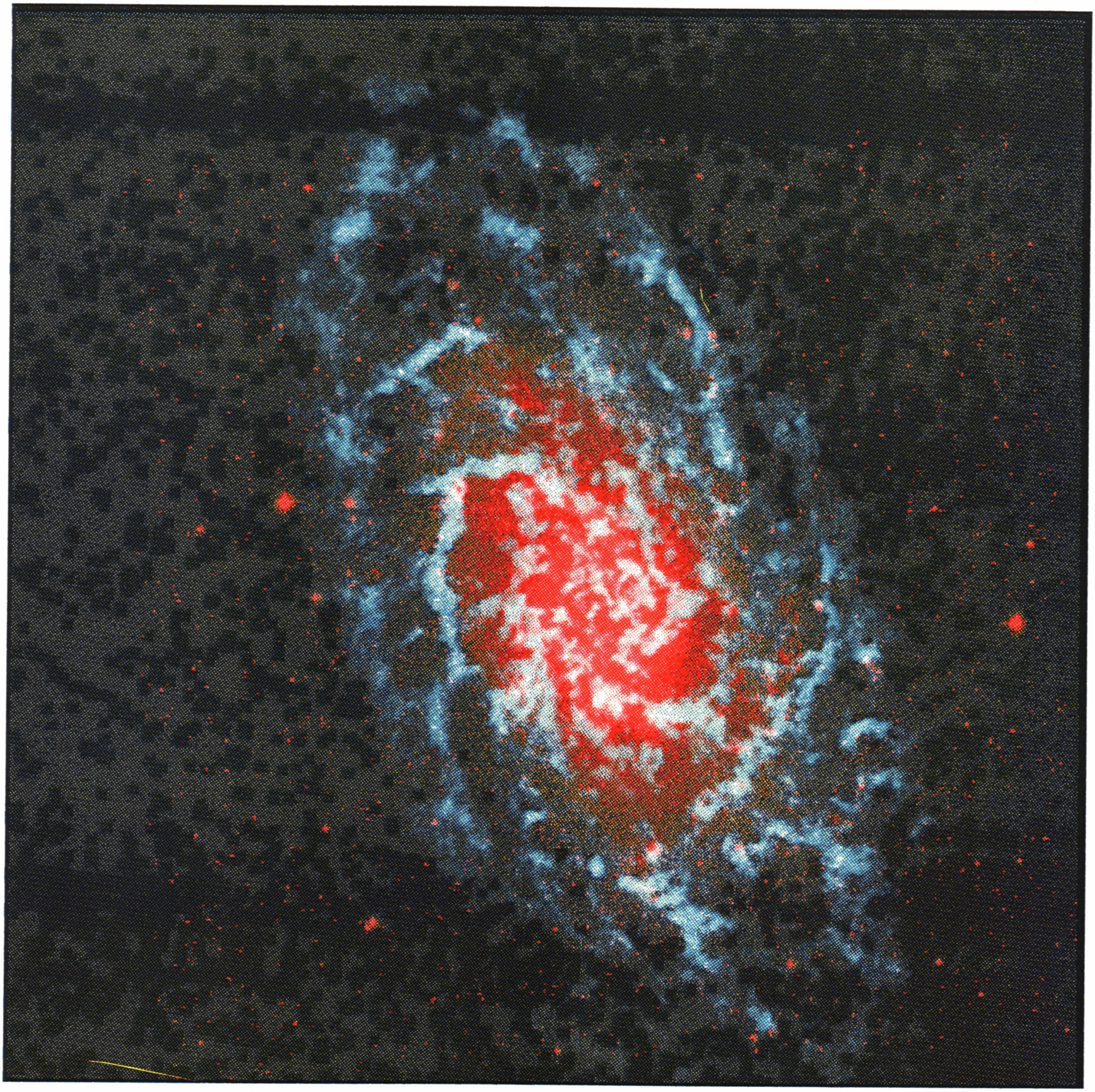


Fig. V-1. An overlay of the optical light from the galaxy M33 (red) and the HI emission (blue) from this galaxy.

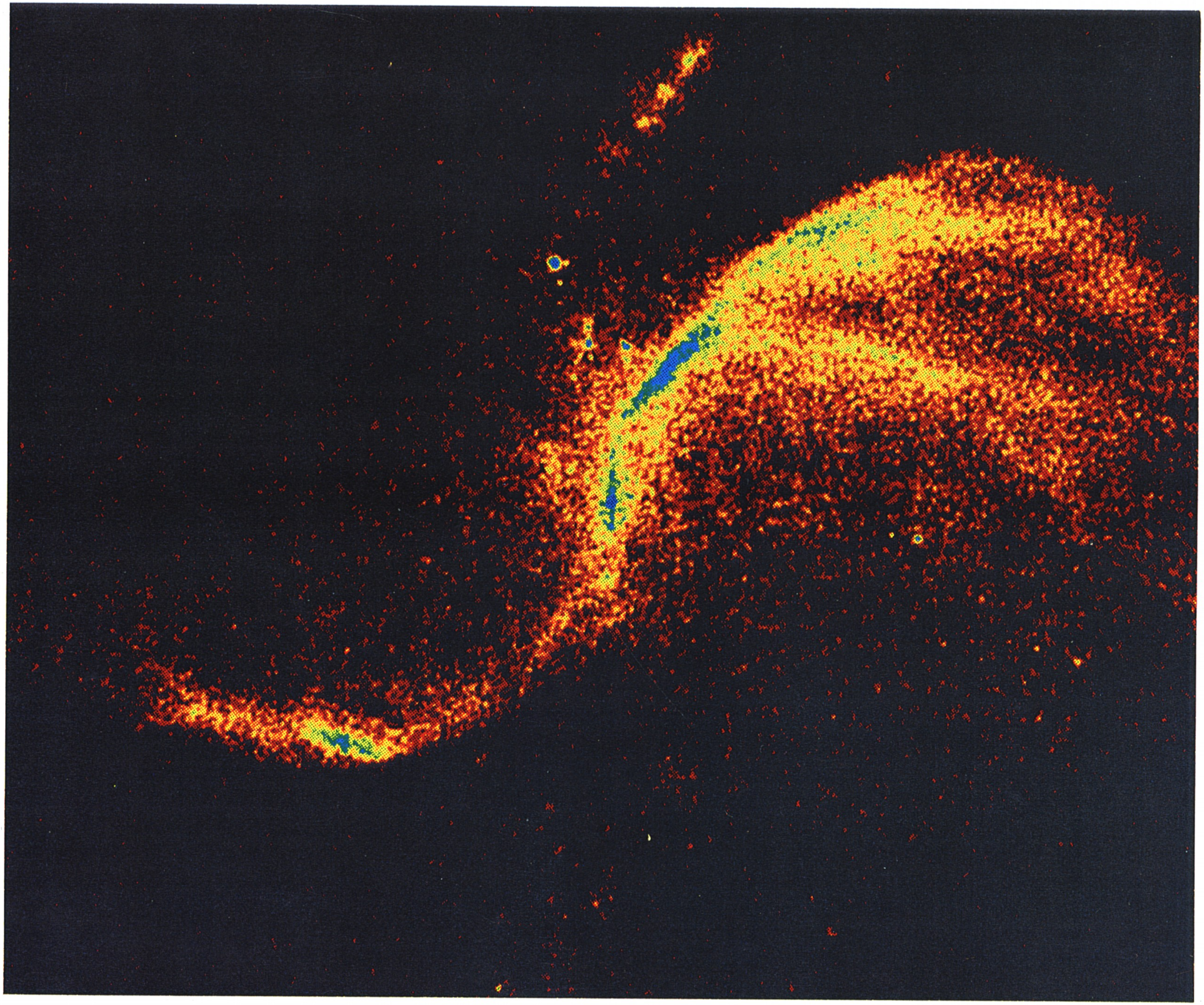


Fig. V-2. A VLA image of the radio galaxy NGC 4258 that harbors a supermassive black hole at its nucleus.

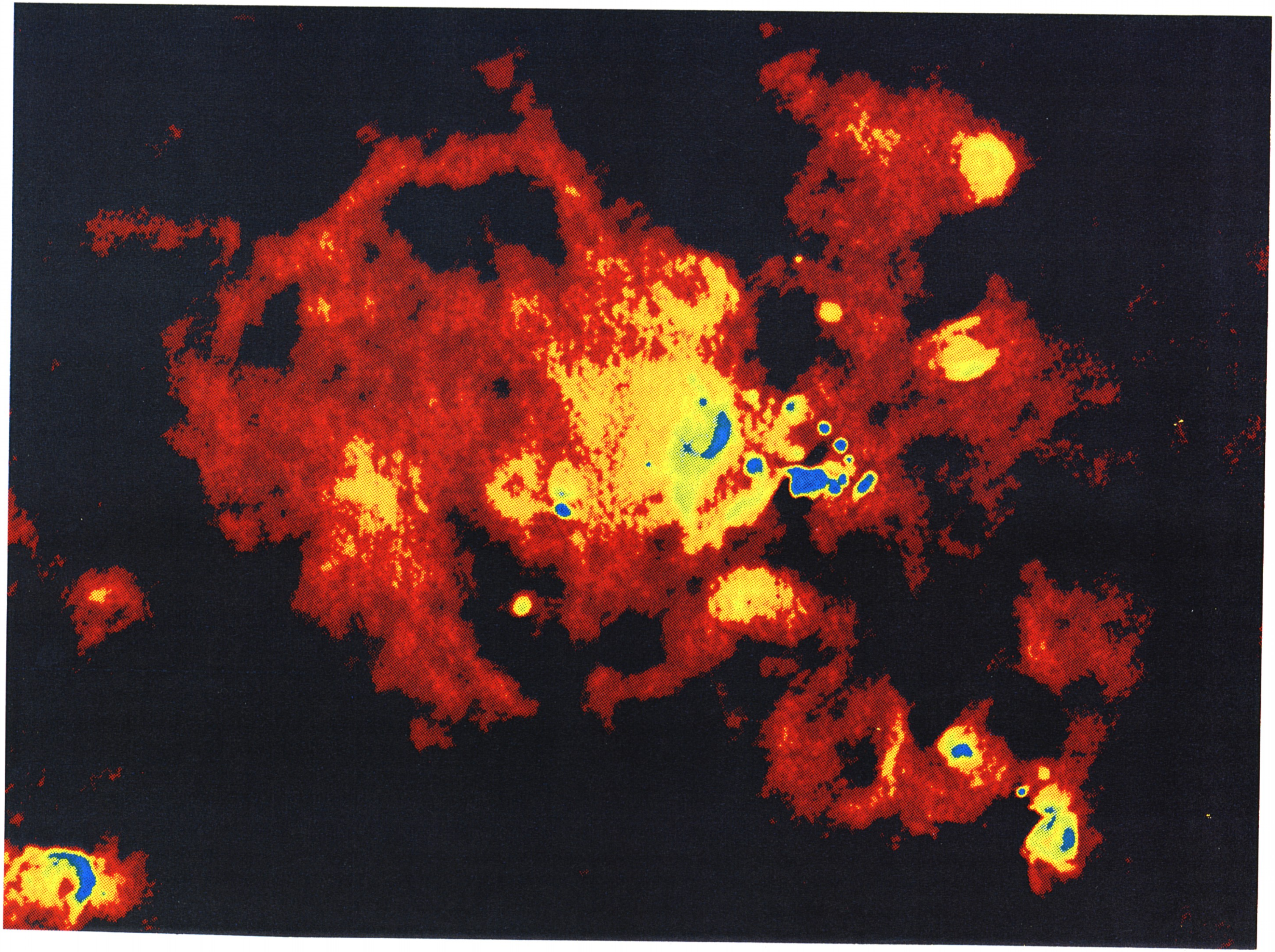


Fig. V-3. The radio continuum emission from the W49 star forming region.

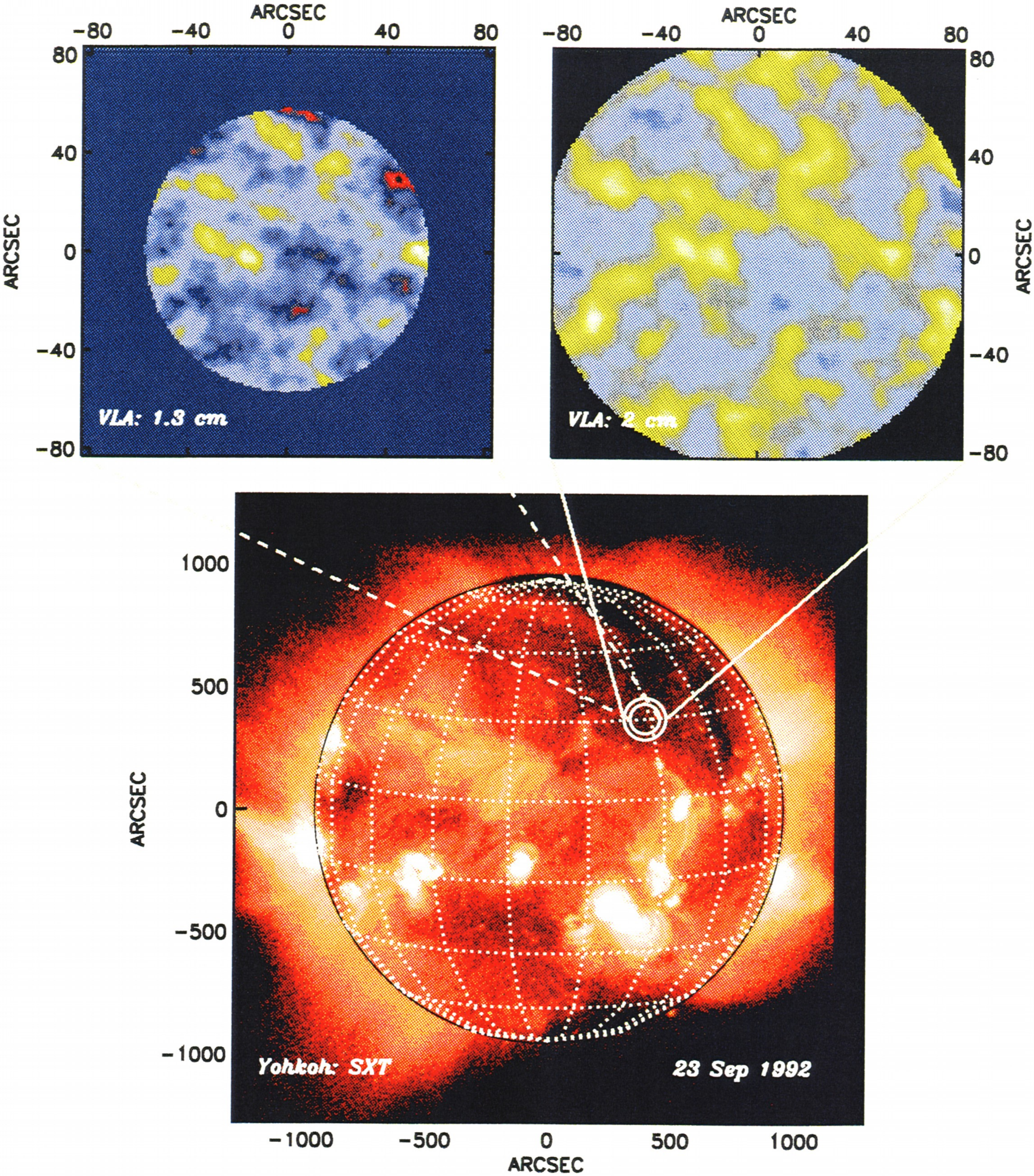


Fig. V-4. A montage showing the x-ray image of the solar disk (lower panel) and selected VLA images of quiet sun regions made simultaneously with the x-ray image.

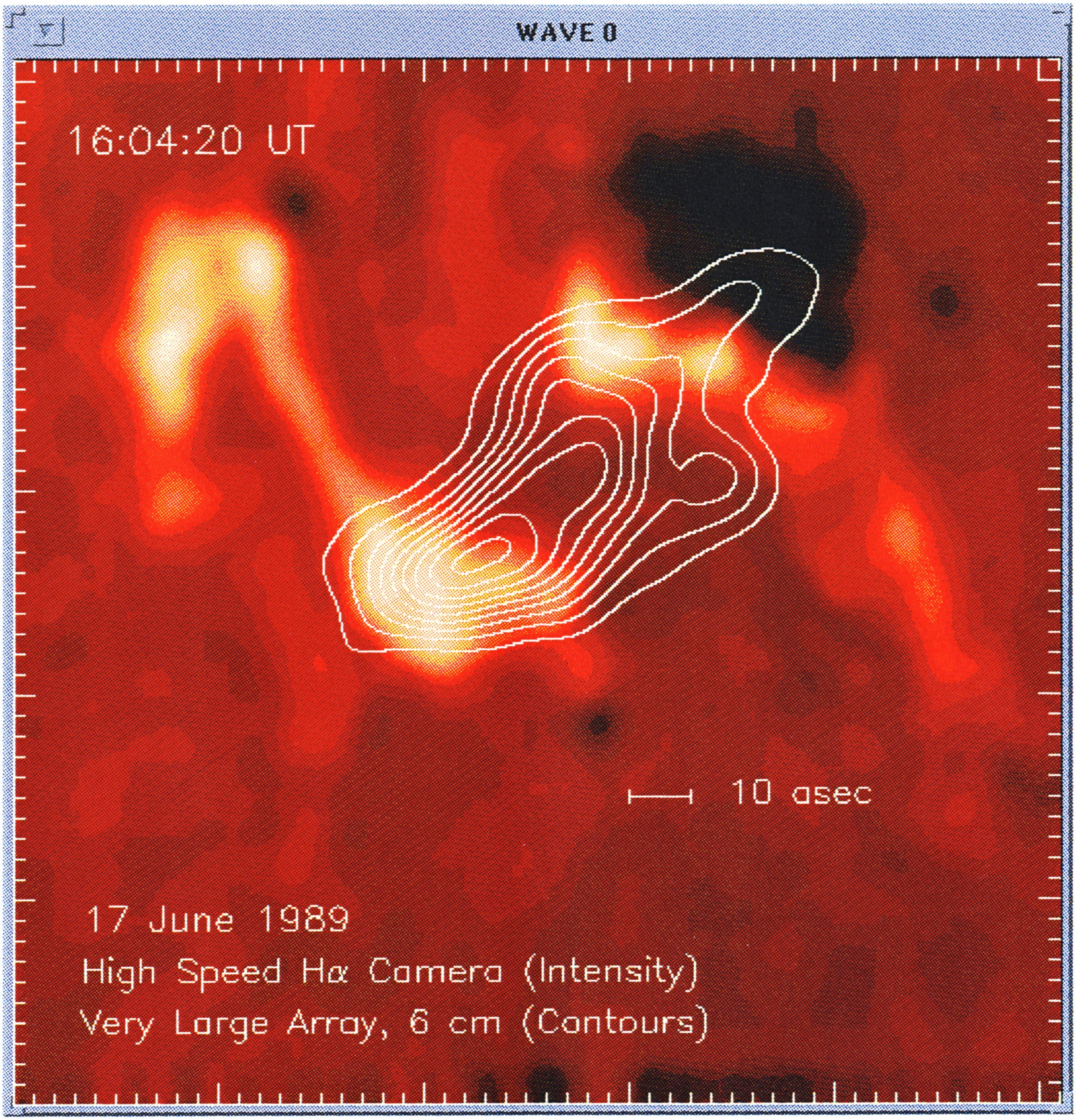


Fig. V-5. The VLA radio emission (contours) associated with a solar flare. The radio emission region extends between two sun spots of opposite polarity.

supergranular cells and has a highly super-thermal brightness temperature. The second figure, Figure V-5, is one frame of a VLA movie of the sun. The background image in this figure is an H-alpha image and the radio contours can be seen connecting two magnetic footprints of opposite polarity. The radio source bridges the conjugate footprints; this combined image points us to the physical explanation for the radio emission.

The VLA, perhaps surprisingly, can also be used to study the solar wind. The technique in this case is to observe extragalactic radio sources near the ecliptic. As the sources appear near the sun, they are broadened by scattering in the magneto-ionic solar wind. The effect of the scattering depends on the turbulence and anisotropy of the turbulence. In Figure V-6 we show the apparent angular diameter of a few radio sources observed near the sun. The fact that their apparent angular sizes are elliptical, not spherical, tells us that the turbulence in the wind is anisotropic, being greatest in a radial direction outward from the sun. The fact that the scattering is largest at the equator of the sun tells us that the solar turbulence is a minimum at the poles. Observations such as this are the only ground-based complement to the *in-situ* measurements made by spacecraft.

Finally, over the period of the long range plan a complete VLA survey of the sky will be made fully available to *armchair* astronomers everywhere. When complete the NRAO/VLA sky survey (NVSS) will have more than two million sources accurately cataloged with position and 1.4 GHz flux density. Figure V-7 illustrates the portions of the sky complete in 1996 and the work yet to be done. A typical NVSS field is shown in Figure V-8. As the data are being taken, the survey is made available on-line via the WWW. It is likely to be a valuable resource for many years.

2. Overview of the VLA Upgrade Project

The Very Large Array has passed the fifteenth anniversary of its dedication. Conceived in the 1960s, constructed during the 1970s, and dedicated in 1980, the VLA is a successful and extraordinarily productive radio telescope. It is used by more than 600 investigators from more than 150 institutions every year. There is every indication that demand for the VLA will continue, owing both to its unique capabilities and to the fact that it provides the radio observations at arcsecond angular resolution needed for the interpretation of observations made at optical IR and X-ray wavelengths. Modern technology can vastly increase the capabilities of the VLA and the time has come for us to upgrade the VLA with modern electronics to open up new, exciting avenues of research which cannot be pursued with the current instrument.

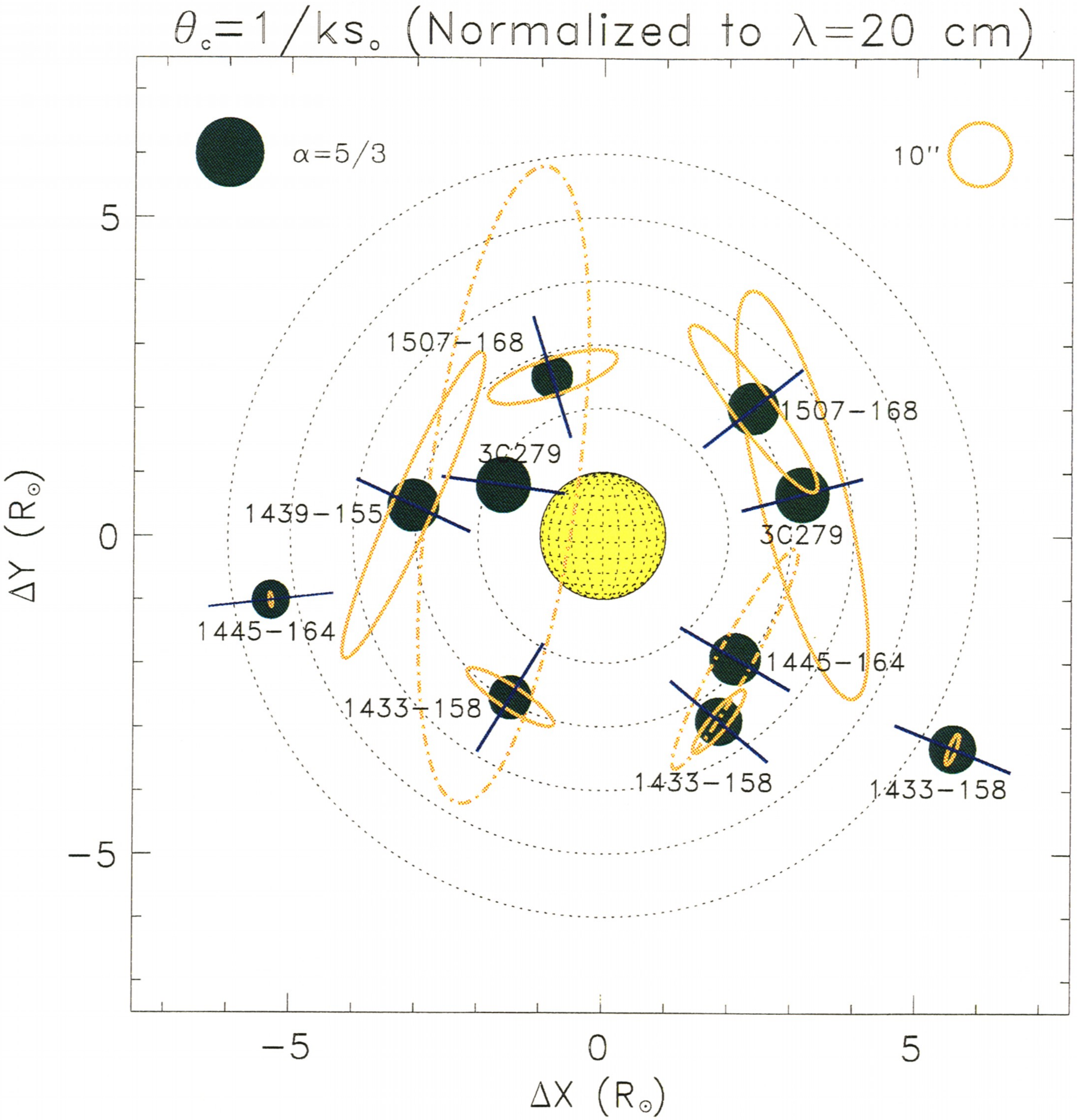


Fig. V-6. The measured scattering size of radio sources as they pass near the limb of the sun. The orange ellipses illustrate the observed source size resulting from scattering.

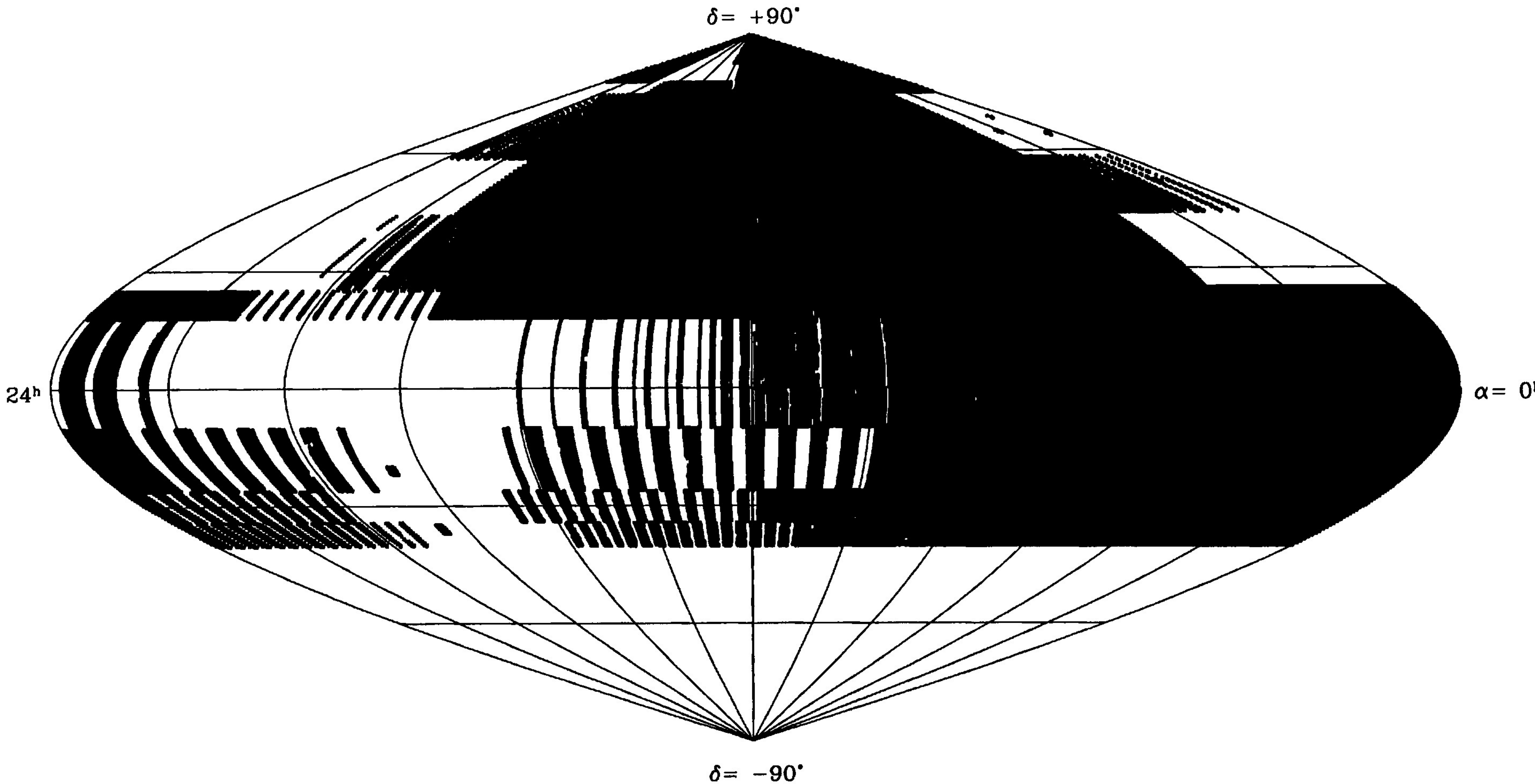


Fig. V-7. Present (May 1996) coverage of the NVSS sky survey. Regions shaded are complete.

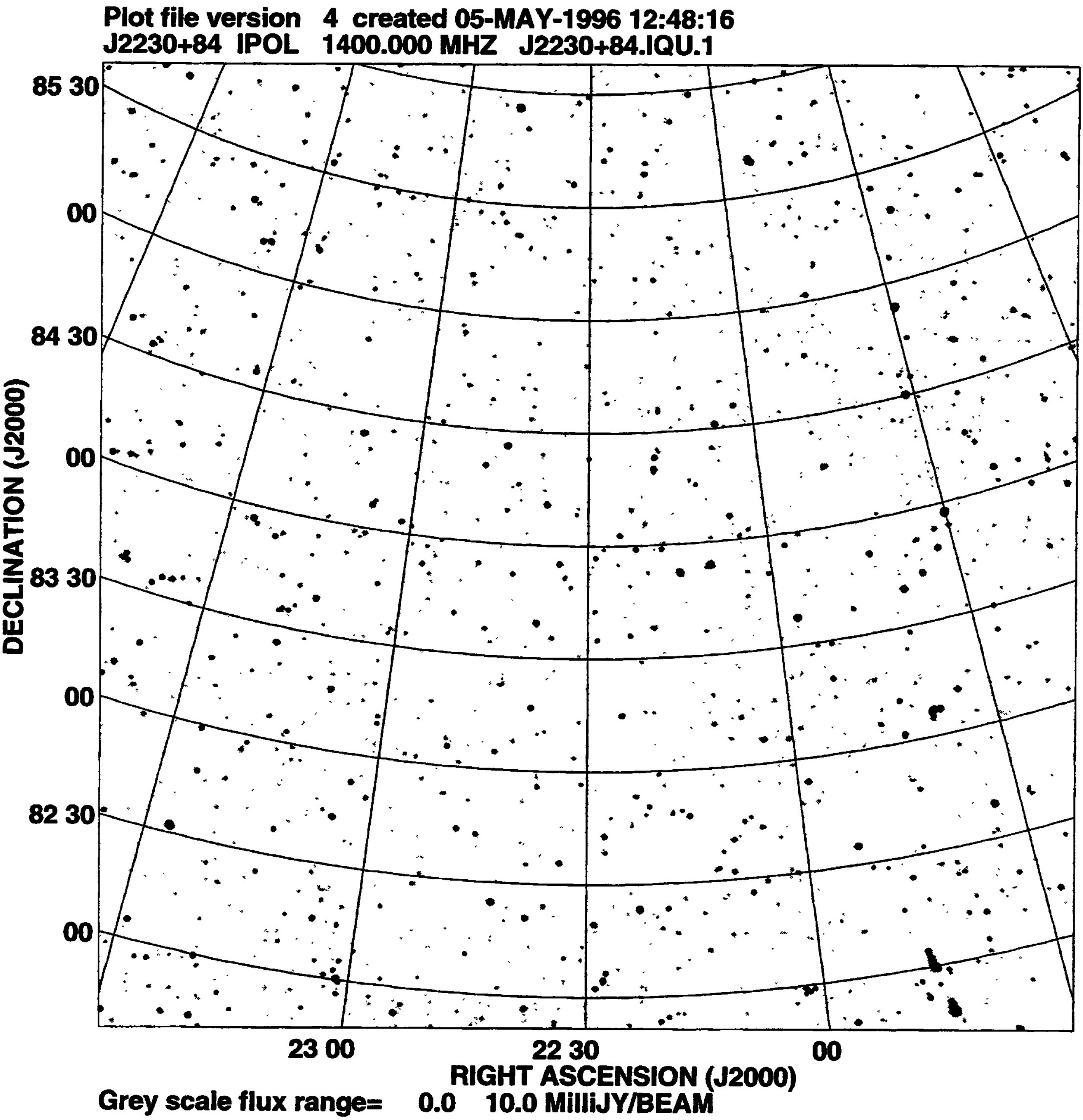


Fig. V-8. An example of the sources detected in a typical region of sky.

Over the years various upgrades have been made to the VLA. Some of these were designed into the instrument at the outset (e.g., the expansion from two to four IFs in 1983 and the expanded support of spectral line modes in 1988). Others arose as an extension of the original design (e.g., the 90 cm, 3.6 cm bands and 7 mm. Still others came from advances in available technology (e.g., the 20 cm receiver upgrade).

Even so, the VLA is an aging instrument. Its basic design is based on technology available in the 1970s. Since that time, major technical improvements have been made in receiver components, correlator design, and the transmission of broadband signals, rendering many elements of the VLA obsolete. Furthermore, many components are becoming increasingly vulnerable to failure – and are increasingly difficult to repair or replace.

3. Technical Summary of the Upgrade

The VLA Upgrade will lead to significant gains in four broad areas: sensitivity, frequency coverage, spectral line capability and angular resolution. As presently conceived, the VLA upgrade includes the following key elements:

- Replace most of the VLA receivers to achieve lower noise temperatures and a much wider bandwidth ($\approx$ 1 GHz/polarization), and add two or three new observing bands.
- Replace the buried waveguide with a fiber-optics data transmission system to transmit the broadband signals.
- Design and construct a new correlator to process both broadband continuum signals ($\approx$ 1 GHz/polarization) and to provide improved resolution and flexibility for spectral line work. The new correlator will support a larger number of antennas ($\geq$ 32).
- Add antenna pads in support of a super-compact array, the E configuration, for improved sensitivity to low surface brightness emission.
- Establish a fiber optics link between the VLA and nearby VLBA antennas. Add four or more new antennas in order to establish baselines intermediate in length to those in the VLA and VLBA, also linked to the VLA by optical fiber.

The impact of these improvements will be enormous. The continuum sensitivity of the instrument will improve by more than an order of magnitude in some bands, new and powerful spectral observations will be possible, and new areas of the frequency domain will be opened for exploration. Furthermore, with the addition of new antenna elements, the angular resolution of the VLA can be greatly improved. These improvements will allow the VLA to retain its status as the premier aperture synthesis telescope well into the next century.

Improved Low Noise Receivers

A gradual upgrade to the VLA receiver systems has been going on since the early 1980s. For several years this involved installing better low noise amplifiers in the existing receivers. More recently, a new style receiver was introduced using the VLBA design in which the receiver is attached directly to the feed and the polarizer is cooled in the cryogenic dewar. This reduced the noise contribution from the polarizer and eliminated long, ambient temperature waveguide runs that added to the system temperature.

The VLBA style receivers are now used at 1.4 GHz, 8.5 GHz, and for the thirteen antennas operating at 45 GHz on the VLA. These receivers will remain with perhaps only minor modification. The greatest improvement in system temperature can be made in the 5 GHz, 15 GHz, and 22 GHz bands using the VLBA style receivers and modern HFET amplifiers. Completely new receivers will be built for these bands. Implementation of such receivers should reduce the system temperatures at these bands by up to a factor of three.

The new receivers will provide ≈1 GHz per polarization bandwidth, needed for continuum sensitivity. They also will tune a wider frequency range to permit the study of new spectral lines whose astrophysical significance was unknown when the VLA was first built. The frequency range in the 5 GHz, 15 GHz, and 22 GHz bands will be extended. A redesign of the 1.5 GHz feed will likely be done to permit observations at lower frequencies.

At present, only ten VLA antennas are outfitted for 45 GHz operation; this band would be made available on all antennas as part of the upgrade.

The improved low noise receivers packaged independently like the VLBA receivers will contribute significantly to improvements in the fidelity of VLA images at all frequencies. Not only will the lower noise figure of the new receivers make for improvements in sensitivity but the greater gain stability of the HFET amplifiers and greater phase stability resulting from the rigid receiver mounts with short waveguide runs will make for dramatic improvements in calibration accuracy and hence image fidelity. These improvements can be illustrated in a quantifiable way. Figure V-3 is an image made of the W49 star forming region in which a large collection of spatially complex, but independent HII regions, are visible. This image was made with the 8 GHz VLBA style receivers. Previous VLA images of the same region made with the older style 5 GHz receivers failed to distinguish many of the various HII regions as separate entities. Just as the science realized here with the new receivers changes with the improved technology so also we expect to see similar improvements at the other VLA observing frequency bands with the new receiving equipment.

New Observing Bands

Two new receiver systems would be added at the Cassegrain focus 2.5 GHz (S band) and 33 GHz (Ka band). These will open new molecular line observations to the VLA (e.g., redshifted CO, at Q-band), improve rotation measure studies, and permit the VLA to participate in bistatic planetary radar observations with the Arecibo Observatory. The S-band system should be the most sensitive system for study of steep spectrum, nonthermal sources. Table V-1 summarizes the proposed siting of new and upgraded VLA observing bands at the Cassegrain focus.

Less well defined are prime focus receiver systems. At present, the 333 MHz system is located at the prime focus, as is a 74 MHz system on eight antennas. Three possibilities for prime focus systems have been discussed.

- The addition of a new receiver system covering 580-640 MHz (matching the VLBA).
- A broadband UHF system covering $\leq$ 150-600 MHz.
- A sensitive 800-1200 MHz system.

Table V-1. VLA Upgrade Proposed Observing Bands

Band	Range (GHz)	Bandwidth (GHz)	BW Ratio	
L	1.20 - 1.80	0.60	1.46	Upgrade
S	2.20 - 3.40	1.20	1.55	New
C	4.80 - 7.20	2.40	1.50	Upgrade
X	8.00 - 12.0	4.00	1.50	Upgrade
Ku	12.0 - 18.0	6.00	1.50	Upgrade
K	18.0 - 26.5	8.50	1.47	Upgrade
Ka	26.5 - 40.0	13.50	1.50	New
Q	40.0 - 50.0	10.0	1.25	Complete

Table V-2 presents a comparison of the continuum sensitivity of the current instrument to that achievable through the upgrade. Fairly realistic assumptions about usable bandwidth have been made and an atmospheric contribution has been added where relevant. The number under ΔS refers to the continuum sensitivity in μJy/beam achieved in twelve hours integration, summing over two orthogonal polarizations. The total bandwidth assumed for 90, 50, 30, 20, and 11 cm is 50, 100, 200, 500, and 1000 MHz, respectively. All other estimates assume 2 GHz net bandwidth.

The new observing bands, particularly the continuous frequency coverage shortward of 1 cm wavelength will open up the capability of the VLA to study objects emitting much of their energy by thermal processes. Two examples of objects which will be amenable to study with the upgraded VLA are protoplanetary disks and minor planets in the solar system.

Table V-2. VLA Sensitivity

	Upgraded VLA		Current VLA	
Band (cm)	T_{sys} (K)	ΔS (μJy)	T_{sys} (K)	$\Delta S_{current}$ (μJy)
90	80-135	40-70	150	120
50	45-90	13-25	-	-
30	25-32	5.3	-	-
20	30	2.7	33	6.0
11	31	1.9	-	-
6	29	1.3	45	6.7
3.6	31	1.3	31	4.4
2	37	1.7	110	20
1.3	50-70	2.6	160	37
0.9	38	2.0	-	-
0.7	55	3.5	80	165
0.6	170	15	-	-

Young stars are expected to form surrounded by protoplanetary disks, flattened structures of gas and dust from which planets form. These disks can be studied with unprecedented angular resolution with the upgraded VLA. In particular, the upgraded VLA is the only instrument other than the MMA capable to observe the inner few AU of the disk, the region where terrestrial planets are formed, since the disks should be transparent at 45 GHz.

Present estimates suggest that within 200 pc of the sun there are about 100 protoplanetary disks with total 45 GHz flux densities of the order of 1 mJy. The disks are expected to have diameters of about 100 AU (0.5 arcsec at 200 pc). In the A array an angular resolution of 0.05 arcseconds can be achieved at 45 GHz, equivalent to a dimension of 10 AU. Within a beam of 0.05 arcseconds, about a flux of 0.1 mJy/beam is expected.

The full 45 GHz upgrade will provide a factor of 36 improvement over the present system (a factor of three for all 27 antennas, two from improved aperture efficiency, three from a total bandwidth of 2 GHz, and two from better receivers). In speed, this represents an improvement of 1300. In a 12-hour on-source integration, the upgrade will bring the rms noise from 0.2 mJy/beam to 5 microJy/beam, making it possible to image the disks with a signal-to-noise ratio of 20 in this time period. At 45 GHz and with the largest VLA configuration, a technique to correct for atmospheric phase noise becomes imperative. Schemes such as the fast switching or accurate total power measurements would be explored to provide phase stability.

Thermal emission has been detected from the four largest asteroids: Ceres, Pallas, Vesta, Hygiea, at wavelengths from 1 mm to 20 cm and from a few smaller asteroids at 2 cm wavelength. Such measurements place constraints on the thermal and electrical properties of those objects surface layers. The existing observations indicate that the asteroids studied so far are covered with fine grained regoliths, which are expected to result from meteoroid bombardment (sand blasting) of the surfaces over hundreds of millions of years. Differences in the microwave spectra of Ceres, Pallas, Vesta, and Hygiea suggest variations in the dielectric properties of those regoliths and/or variations in the regolith thicknesses. However, those few objects represent just a tiny fraction of the thousands of main-belt asteroids, most of which are beyond the detectability of the current VLA. In addition, there is a gap in the wavelength coverage from 1 mm to 1 cm. Over this range, the spectra show a distinct drop in brightness temperature. The proposed VLA upgrades in continuum sensitivity and wavelength coverage should make a large number of these objects detectable at several wavelengths. Of particular importance is the 45 GHz which fills the 0.1-1.0 cm wavelength gap.

The new IF/LO system will allow the transmission of wideband signals, and the wider IF bandwidth will bring with it increased sensitivity. The chief limitation on observational stellar radio astrophysics is sensitivity. Consequently, one of the most important elements of the proposed upgrade for stellar research will be the order of magnitude improvement in sensitivity afforded by the improved receivers and greater bandwidth. Several hundred stellar radio sources are now known. The sensitivity upgrade to the VLA will increase this number by over an order of magnitude. Sensitivity at the micro Jansky level has the potential to increase the number of radio detected stars from the current value of a few hundred to thousands or, perhaps, tens of thousands. This phenomenal increase cannot help but revolutionize the field of stellar radio astronomy. New classes of radio stars and previously unknown phenomena relating to stellar radio emission are almost certain to be discovered.

A New Correlator

The current VLA correlator is limited to a bandwidth of 4x50 MHz. A new correlator is needed to process the 2 GHz of bandwidth and to achieve the increase in continuum sensitivity and instantaneous spectral coverage. Moreover, the current correlator limits the type of science which can be done due to its limited spectral resolution at wide bandwidths. With a 50 MHz bandwidth, the VLA can only produce eight spectral channels in total. With so few channels, wide field imaging at low frequencies, and searches for redshifted spectral lines are extremely inefficient. Similarly, a 50 MHz bandwidth at high frequencies (e.g., 350 km/s at 43 GHz) makes observations of extragalactic lines difficult, if not impossible, and excludes many components of those molecular lines which are split into multiple transitions.

Current specifications for the correlator call for a minimum of 512 channels in each of the four 500 MHz IF channels returned from the antennas, although the identification and excision of radio frequency interference may require significantly more channels. The bandwidth of each channel would be adjustable by factors of two over a wide range, allowing widely variable spectral resolution. The spectral resolution should, at least, be comparable to that of the Millimeter Array, of order 0.05 km/s at high frequencies. This represents a factor of three improvement in the spectral resolution on the widest bandwidth now available, and an order of magnitude improvement in the largest spectrometer bandwidth now available. The demands of planetary radar may require even finer spectral resolution, as small as 8 Hz.

The new correlator will be capable of processing data from at least 32 antennas and have sufficient delay to accommodate baselines up to 500 km. The correlator could then process some combination of the 27 VLA antennas, two or three of the innermost VLBA antennas (those at Pie Town, Los Alamos, and Fort Davis), and four or more new antennas on baselines intermediate to those contained in the VLA and VLBA.

Increased Surface Brightness Sensitivity

While the VLA provides four array configurations which cover a wide range of angular scales, the instrument is less than optimum for imaging objects of low surface brightness, often on angular scales comparable to or greater than the size of the primary beam. For resolution corresponding to baselines less than 100 meters, existing or soon to exist single dishes such as the GBT, are well-suited to such work. But for resolution intermediate between the VLA D array (1 km) and 100 meters, there is a gap where imaging is difficult and surface brightness sensitivity is a problem. One possibility is to move the outermost VLA antennas from the D array closer to the array center and create a new, more compact array, the E array, with a characteristic maximum baseline of 300 meters. About nine new stations would be necessary.

Such an E array would double the number of baselines less than 300 meters. This would not only halve the time needed to reach a given surface brightness but also dramatically improve the *uv* coverage on such baselines. Combined with the total power system discussed above, this would make mosaicking practical with beams of four to nine times larger in area than the current D array. The increased brightness sensitivity of the E array will benefit all studies of the galactic interstellar medium as well as studies of extended regions of nonthermal emission such as galactic halos.

Increased Angular Resolution

Recognizing that there is a gap in the *uv* coverage between the maximum baseline lengths sampled by the VLA and the minimum baseline lengths sampled by the VLBA, the addition of four antennas to the VLA is an important second phase to the VLA upgrade project. This neglected part of the *uv* domain – that which is intermediate to the VLA and the VLBA – is currently accessible only to the MERLIN array in Great Britain. With the addition of four new antennas plus the innermost VLBA antennas (at Pie Town and Los Alamos, NM), the VLA's angular resolution could be improved by an order of magnitude in some cases. Its flexibility, sensitivity, and *uv* coverage would be far superior to MERLIN's.

The new correlator should accommodate at least 32 antenna stations, in anticipation of including the Pie Town and Los Alamos VLBA antennas for some experiments via fiber optics links and with the plan of eventually adding the four new antennas. The additional correlator cost is very modest.

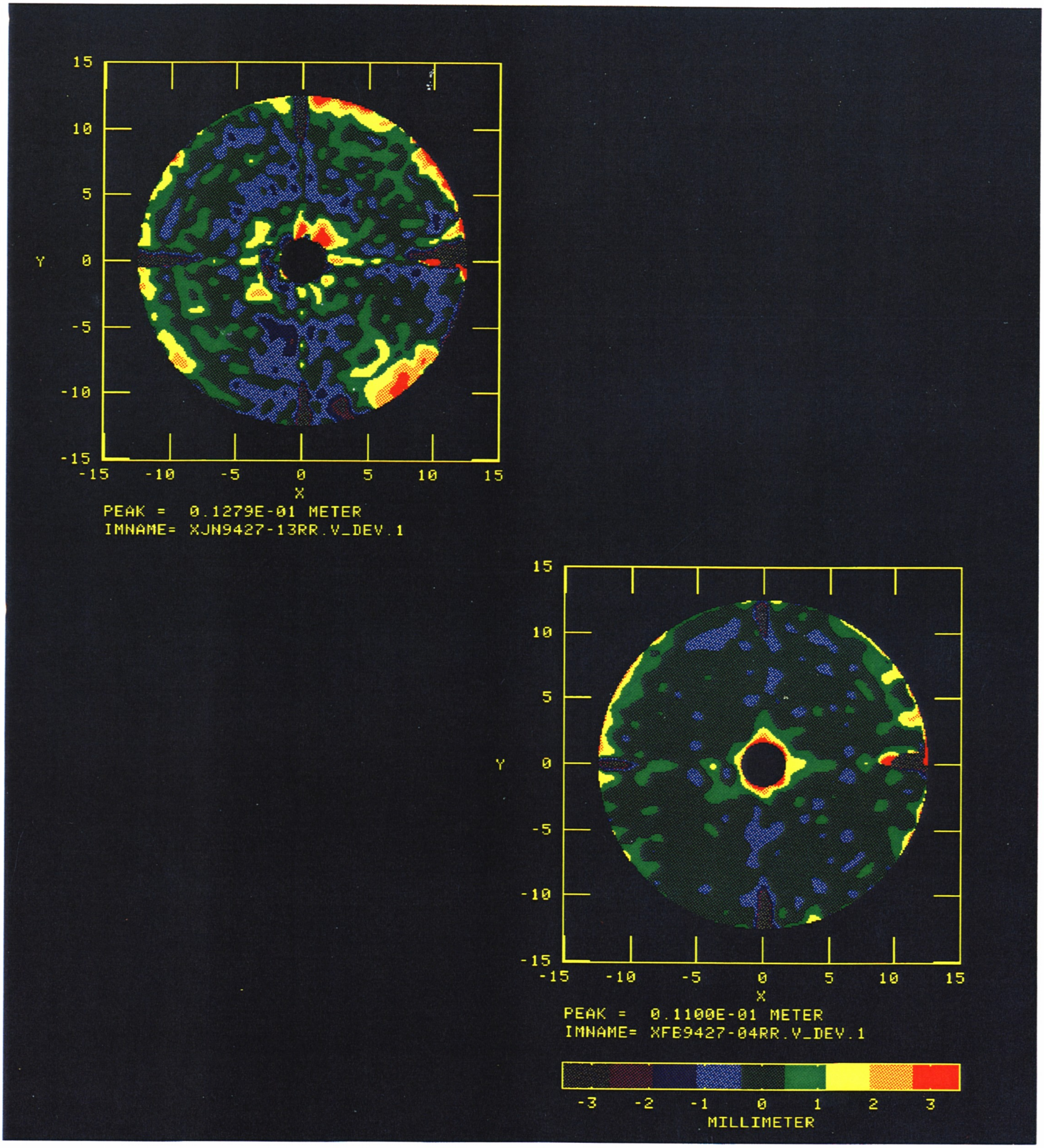
The increased angular resolution provided to the VLA will principally benefit studies of stellar emission (thermal and non-thermal) and studies of the details of extragalactic radio sources. In the latter case, not only is the resolution needed but so also is good imaging capability on the scale of a few to several tens of milli-seconds. This capability will be provided by the new antennas and complementary observations with the existing VLA and VLBA. With it we can expect direct measurements of the velocity of material in radio jets and perhaps even a direct measurement of the Hubble constant.

Antenna Improvements

To increase the VLA sensitivity at the highest frequencies, the surface figure of all the antennas will be reset using holographic maps made at the highest (40-50 GHz) frequencies. An example of one VLA antenna which has been so reset is shown in Figure V-9. One panel of this figure shows the holographic surface irregularities before adjustment was attempted; its rss error is 0.42 millimeters. The other panel is the same antenna after adjustment, where the surface rss has been reduced to 0.17 millimeters. If improvements of this magnitude can be achieved on all the VLA antennas, the array sensitivity will be improved by a factor of two and a half and the observing speed of the array will increase by a factor of six at high frequencies.

4. Cost and Schedule

A detailed plan for the VLA upgrade is being prepared in consultation with interested members of the U.S. scientific community. As one measure to this end a VLA Upgrade Science Workshop was held in Socorro in January 1995. Since then the VLA Upgrade Project has been formally organized with a Project Scientist and Project Engineering Director. Nine working groups are being appointed. A memo series has begun. The goal is to produce a design study by the end of 1997, in time for consideration by the next decadal survey committee.



AIPS User 115 ANT 27 -- BEFORE/AFTER

Fig. V-9. Holographic maps of the surface of a VLA antenna before and after the surface shape has been adjusted.

VI. SOFTWARE DEVELOPMENT AND COMPUTING

1. Overview

Computing lays a vital foundation for scientific research by NRAO users and visitors. Besides the obvious necessity for computer control of the systems that comprise a radio telescope, the use of computers and data reduction systems are essential to translate most of the raw data from radio telescopes into the imagery and other products which lead to scientific results. Significant processing is required before scientific analysis can even begin. In radio astronomy, computer analysis is fundamental to the process, rather than merely being a useful adjunct to scientific analysis. Moreover, owing to the unique application to radio astronomy, the software required for astronomical research must, as a necessity, be written in-house. There are no commercial vendors of radio astronomy research software.

Maintaining observational and scientific capability is the fundamental goal of computing at the NRAO. Staff and visitors at NRAO facilities need access to adequate computing resources, including hardware, software, and personnel support. Constant striving to keep ahead of computing demands at NRAO is essential to meet NRAO's overall goals for supporting astronomical research. Computing systems and software should not be the limiting factor in the science which users are able to accomplish with NRAO facilities. As observational requirements on computing increase (driven by improved observational methods, new technological capabilities, and deepening scientific understanding and knowledge), the Observatory must respond appropriately.

Unfortunately, relentless budgetary pressures over the past few years have resulted in decreased investment in computing at NRAO. The last major investment in computing hardware at NRAO occurred with the completion of the VLBA; significant computer purchases in 1992 and early 1993 were the result. Both 1994 and 1995 have turned out to be relatively lean years for the Observatory, forcing hard choices which ultimately impose limits on the kinds of science which can be accomplished with Observatory facilities.

2. Requirements

There are three principle components to computing support at the NRAO. Highest priority must be given to the first area, namely, computing support for instrument control and operations, including personnel, software development, and operations. Of nearly equal importance are the other two components (1) software development and (2) support for the research activities of visitors and users of the NRAO.

A number of exciting developments at the NRAO will place new demands on NRAO's computing facilities and personnel over the coming few years. Planned instrumental developments and improvements will result in important new scientific capabilities, and will certainly demand improvements in several areas in computing at the observatory for maximum scientific return.

- The demands of the VLBA will continue to grow in the next five years. Typical data sets are up to several gigabytes in size, resulting in many hundreds of images. There will be hundreds of such data sets produced per year. We will continually work on improvements to the computing facilities to avoid limiting the scientific productivity of the VLBA over the next five years.
- The GBT will become operational in early 1997. Computer control of the telescope, the actuators, and the receivers is an enormous task. Efforts are underway to insure that software will be in place to handle GBT data reduction.
- Advanced experiments with the VLA are producing one to two orders of magnitude more data than typical experiments during the 1980's. These sorts of experiments strain the processing facilities (both hardware and software) at NRAO sites or at the user's home institutions. In some areas, the NRAO user community is, in effect, self-limiting its use of NRAO facilities and not tackling scientifically important problems because of limited computing resources in the community.
- Array receivers and rapid imaging techniques, combined with high resolution spectroscopy, are revolutionizing single dish radio astronomy, with data rates two to three orders of magnitude greater than in the past. Hardware to handle these data are not yet in place at the NRAO; necessary software developments have also been delayed.
- Scientific visualization techniques are going to become essential for dealing with the large data volumes from new instruments and receivers. Personnel limitations have prevented any significant work in this area. Two important problems in visualization are already known: the visualization of three dimensional spectral images, and the visualization of large raw data sets for calibration and editing purposes.
- By the end of the period of the long range plan, the MMA will begin interim operations. Investments in computing (hardware, software, and algorithms) will be necessary if the MMA is to maximize its science return. Real-time imaging with the MMA is a scientific necessity which requires improvements in hardware and development of new software and algorithms. During the design phase of the MMA, significant development of advanced computing algorithms for imaging is needed to optimize the design of the MMA.

- Plans to upgrade the VLA will result in a dramatic increase in the VLA's scientific capabilities and place heavy demands on computing to handle the increased data rates. Significant software development will be required to take full advantage of the VLA upgrade, especially in the area of wide bandwidth imaging and large field imaging. Some of these areas could benefit the community today; others are needed to optimize the upgrade plans.

Ultimately, scientific computing is driven by the demands of new instruments and new techniques. The developments above are all placing huge demands on the data reduction facilities at the NRAO and on the personnel involved with software development.

3. Strategy

Computing Hardware

The maximum return from the investment in advanced instruments and facilities at the NRAO will be achieved if adequate investment in computing hardware is maintained. Scientific computers have a useful life of only three to five years, due to the rapid increases placed on computing and to the rapid improvements in available computing capability. In light of this, the NRAO needs to move from a feast and famine approach to a more efficient strategy of continual upgrades and improvements. This strategy will allow us to support the current instruments (VLA, VLBA, 12 Meter, 140 Foot) and also to be prepared for the future instruments: the GBT, the MMA, and the VLA upgrade.

Software Development

The main emphasis in software development at the NRAO has been in two areas: supporting the main NRAO instruments in an operational sense, and developing and supporting software systems for use by users of the instruments in analysis of their radio astronomical data.

An important focus of the imaging and analysis efforts at the NRAO has been aimed at bringing the AIPS++ software into operation (see below), and building on that to provide advanced capabilities needed in all areas of radio astronomy: connected element interferometers, very long baseline interferometry, single dish spectroscopy, and single dish mapping. The Observatory also maintains and distributes to users its current flagship software products, AIPS and UniPOPS. Significant new effort will be directed towards developing the algorithms required by the VLBA and orbiting VLBI software development.

Single Dish Computing

The largest effort in single dish computing is focused on designing and implementing the control system for the GBT. GBT computing is the highest priority in the single dish area. The main analysis package for observational data from the NRAO 140 Foot and 12 Meter Telescopes is the UniPOPS package. UniPOPS is relatively stable, but is inadequate in the face of rapidly developing observing techniques such as on-the-fly mapping or multi-beam observations. Although AIPS++ will deal with these types of new observing within the next two years, this has left a gap in the support of current techniques. On-the-fly mapping at the 12 Meter Telescope is a technique shown to produce wide-field images form the 12 Meter Telescope at millimeter wavelengths that are comparable with VLA long-wavelength images. But they do so at the expense of an enormous data rate and data processing cost. The procurement and personnel plans below address these problems by proposing a sufficient workforce for computing and appropriate hardware upgrading.

The long term strategy for single dish data analysis is clear: single dish data analysis will be an integral part of the AIPS++ package. The benefit of this strategy is that a synergy between the techniques needed for single dish and interferometric analysis will develop. For example, both techniques can produce large three-dimensional spectral image cubes; there will be a large similarity in the analysis and visualization methods needed for such images.

VLA Computing

The most urgent need faced by the VLA is for upgrade and replacement of its on-line control system. The current system is over nine years old, and is starting to show its age in terms of reliability and maintenance costs. The replacement to be implemented over the next few years will be the minimum to keep the VLA operational, but will also provide the foundation needed for the eventual large-scale VLA upgrade.

VLBA Computing

Estimates of the computing requirements for reducing VLBA data were based on a relatively modest model of VLBA observing: detailed images of sources produced from long integration. It now appears that surveys and rapid imaging experiments will be a significant portion of VLBA observing, resulting in up to hundreds of images from a single experiment. VLBA data sets are typically much larger than VLA data sets because of the multiple frequency bands which are used to get wide bandwidth and delays which must be reduced separately for each frequency band. The full impact of VLBA data reduction requirements has not yet been felt, since the VLBA is not yet up to full operational production. The current crop of high-end workstations available at the AOC will be hard pressed to cover VLBA data reduction requirements for the long term. A medium to large VLBA data set will probably require dedicated access to a ~80-100 MIPS machine for several weeks by a single user. There are currently only five such machines available at the AOC, and two in Charlottesville; advance sign-up lists for those machines are two months long.

The AIPS++ Project

The Astronomical Information Processing System (AIPS++) is a software system designed primarily for astronomical data analysis. NRAO's partners in the development of AIPS++ are: Australia National Telescope Facility, Australia; Berkeley-Illinois-Maryland Association, USA; Herzberg Institute for Astronomy/Dominion Radio Astrophysical Observatory, Canada; Netherlands Foundation for Research in Astronomy, the Netherlands; Nuffield Radio Astronomical Laboratory, UK; and the National Center for Radio Astrophysics, India. Inside NRAO, the Project is organized as a construction project of limited duration. The goal is to replace and extend the functionality of the AIPS system within five years. In 1996, AIPS++ will be used for a number of time-critical applications inside the consortium observatories. In 1997, a first full release of AIPS++ will be made with initial functionality for single dish and connected element array processing. In later years, the functionality will be expanded to include very long baseline interferometry and other complex applications. The specific plan includes the following milestones: (1) in late 1997 provides support for the GBT commissioning with a fully capable single-dish analysis package; (2) in 1998 the VLBI calibration and imaging tasks will be completed; and (3) in 1999 all the remaining user functionalities of previous analysis packages, such as AIPS, Miriad, NewStar, will be incorporated in AIPS++. Subsequently, the capabilities of the system will be expanded to completeness. As the system becomes more and more complete, personnel currently working to support AIPS operations will be transferred over to the operational support of AIPS++.

VII. ELECTRONICS DEVELOPMENT

The NRAO Central Development Laboratory (CDL) is engaged in the design and evaluation of devices that are of potential benefit to the operation or performance of the NRAO telescopes. The CDL works collaboratively with the engineering staff at all the observing sites, and for this reason the range of technical tasks undertaken at any particular time at the NRAO involve work principally done at the sites as well as work physically done at the CDL. Much of the electronics development that will be accomplished in the next five years is covered elsewhere in this report in association with the discussion of the long range plans for the individual NRAO telescopes. Specific development work at the CDL will include the following:

- Evaluation of pseudomorphic HFET amplifiers;
- Advanced design and contract fabrication of SIS mixers;
- Prototype and test of 86 GHz HFET-based receivers for the VLBA;
- MMA technology development and demonstration tasks.

HFET Amplifiers

The theoretical performance of small area HFET amplifiers indicates that the performance of such devices should be such as to provide a device noise figure of less than 10 K throughout the centimeter wavelength range. For radio astronomy applications, this will make the HFET's competitive with the best maser receivers. At still higher frequencies, at the long millimeter wavelengths, the HFET amplifiers may be superior to SIS mixers. Figure VII-1 is an illustration of how the best NRAO HFET amplifiers compare with the best NRAO SIS mixer receivers. The crossover point appears to be near 100 GHz.

At the NRAO we are attempting to achieve the expected HFET noise figures at the highest frequencies. By means of a contract with Hughes Research Laboratories, we had fabricated two wafers with nearly 6500 InP HFET devices with gate widths suitable for applications from 1 to 100 GHz. Over the course of the next five years, we expect to incorporate these new devices in receivers for the VLA, VLBA, GBT, and for the 3 mm MMA receiving system.

SIS Mixers

The long-standing collaboration between the NRAO and the University of Virginia Semiconductor Devices Laboratory is once again yielding high quality Nb SIS devices. We use the devices in receivers for the 12 Meter Telescope covering 68-300 GHz, and we are experimenting with radical new tunerless designs capable of meeting the demanding MMA

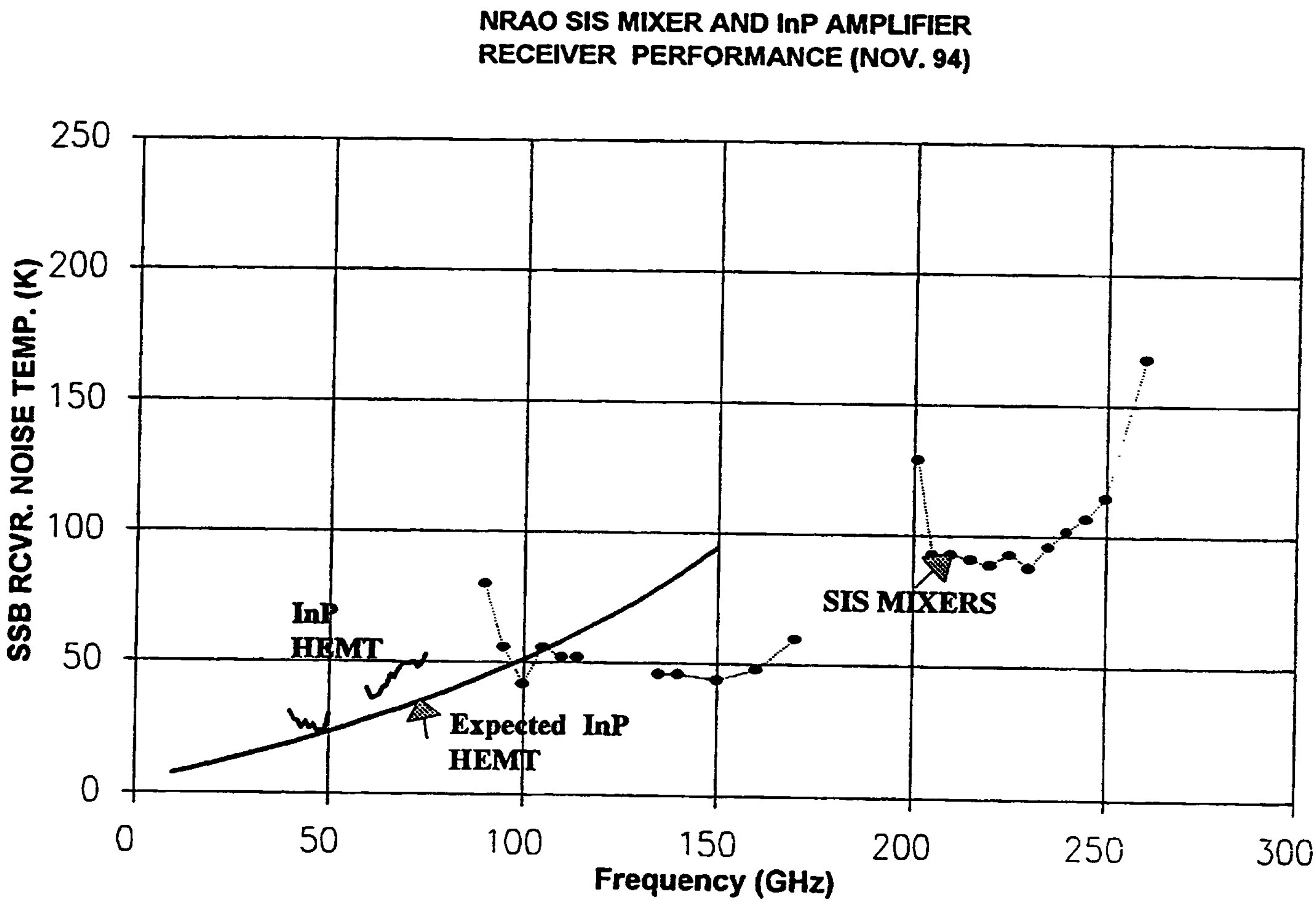


Figure VII-1. NRAO receiver performance.

specifications for sensitivity and wide bandwidth. Increasingly, it is work preparatory to the MMA that is the focus of the NRAO SIS design effort. The important goals in this respect are:

- Evaluation of the feasibility of building single sideband SIS mixers with no active mechanical tuning or rejection elements. If successful, such mixers will enhance the sensitivity of the signal sideband by eliminating the sky noise contribution from the unwanted sideband;
- Develop an integrated SIS mixer and IF amplifier for wider IF bandwidth. A secondary goal of this project is to simplify the manufacture of SIS mixers for greater reproducibility and easier maintainability.

In anticipation of the MMA needs for very low noise SIS receivers to take advantage of the exceptionally good atmospheric conditions on the MMA sites under study, we have begun a collaboration with the JPL semi-conductor devices laboratory for fabrication of image separating, balanced, SIS mixers.

With noise temperatures of SIS receivers now in the range 2-4 times the photon temperature ($h\nu/k$), the overall sensitivity of radio astronomy measurements can be seriously degraded by atmospheric noise, and sometimes by noise from the local oscillator source. In spectral line measurements, atmospheric noise in the unwanted (image) sideband can be eliminated by using an image separating scheme. To reduce local oscillator noise, balanced mixers can be used.

It is possible to realize image separating and balanced mixers using quasi-optical or waveguide RF circuits, but they are difficult to fabricate and bulky. We believe it is now practical to include the necessary signal and LO power dividers, couplers, and cold loads with the SIS mixer on the same quartz substrate. The complete image separating or balanced mixer can be fabricated using a standard niobium SIS mixer fabrication process with one or two additional layers.

We have designed a single-chip balanced and image separating mixer for 200-300 GHz. The circuits are designed using a modified form of coplanar transmission line which has a convenient range of characteristic impedances while minimizing coupling to adjacent circuit elements. It is hoped ultimately to combine the image separating and balanced designs to make a balanced image separating mixer on a single chip so as to produce exceptionally low-noise millimeter and submillimeter receivers.

86 GHz VLBA Receiver

At an observing frequency of 86 GHz, the VLBA has an angular resolution twenty times better than that at 5 GHz and better even, by a factor of two or three, than the resolution of the current generation of space VLBI missions, VSOP and Radioastron, at their *workhorse* frequency of 5 GHz. With the 86 GHz resolution of less than 100 micro-arcseconds, the accretion disks of active galactic nuclei in the local universe will be resolved at a frequency at which they are transparent. This is the right resolution at the right frequency.

Two prototype 86 GHz receivers for the VLBA are under construction now. They incorporate the Hughes InP HFET amplifiers and are both dual polarization receivers. In 1996 the receivers will be installed on two of the VLBA antennas for tests. If successful, the entire VLBA will be equipped with similar receivers on an incremental basis over the next four years.

MMA Development Tasks

Much of the SIS emphasis and a significant fraction of the effort on high frequency HFET amplifiers is done in the expectation of the needs of the MMA. The MMA focus on multiples of forty of all the key components of a radio telescope brings to the fore the need to design simple devices that are easy to build, replicate, and maintain. While these design parameters have always been important in other NRAO applications, they become foremost for an instrument as complex as the MMA and one likely to be located on a very remote site. The need for MMA design simplification extends also to the need for a simple multiplier design and a straightforward calibration system.

In collaboration with the University of Michigan, we are engaged in design work on a 60-90 GHz monolithic multiplier that, if successful, may be appropriate for the MMA local oscillator multiplier. A second collaboration, this time with both the University of Michigan and the University of Virginia, is working to develop a calibration system for the MMA. The problem is that tunnel diode noise sources that are currently used successfully at centimeter wavelengths do not give sufficient signal power above 25 GHz and hence are inadequate for the MMA. In the course of this long range plan we will jointly explore use of resonant tunnel diode structures as calibration noise sources. If the design and tests go well, MMA fabrication facilities will be developed at one of the participating universities.

Finally, in recognition of the fact that the MMA local oscillator system is a critical, costly, and potentially high maintenance part of the MMA, we have explored alternatives to the multiplied Gunn system used universally at millimeter and submillimeter wavelengths. A very promising alternative is to use the beat note of two solid-state infrared lasers as the MMA local oscillator. This idea is being pursued as a research project in Tucson with the expectation that a choice on the technology of the MMA local oscillator can be made by 1999.

VIII. BUDGET AND PERSONNEL PROJECTIONS

(NSF Funds, $ in Thousands)

	1997	1998	1999	2000	2001	2002
OPERATIONS						
Base Operations	$29,940	$31,600	$32,865	$34,115	$35,135	$36,190
Research & Oper. Equip.	60	1,400	1,500	1,500	1,600	1,600
NSF Operations	$30,000	$33,000	$34,365	$35,615	$36,735	$37,790

NEW INITIATIVES (Major Res. Equip.)						
MMA Design & Dev.	--	$ 9,600	$ 9,800	$6,735	--	--
MMA Construction	--	--	--	--	$25,000	$41,000
VLA Upgrade	--	--	--	2,500	3,000	3,000
Total New Initiatives	--	$ 9,600	$ 9,800	$9,275	$28,000	$44,000

Personnel Projection (Full-Time – Year End Ceiling)

Operations	396	391	391	396	396	396
MMA Design & Dev.	--	44	48	49	--	--
MMA Construction	--	--	--	--	55	55
Non-NSF Research	18	18	18	7	7	7
Personnel Totals	414	453	457	452	458	458