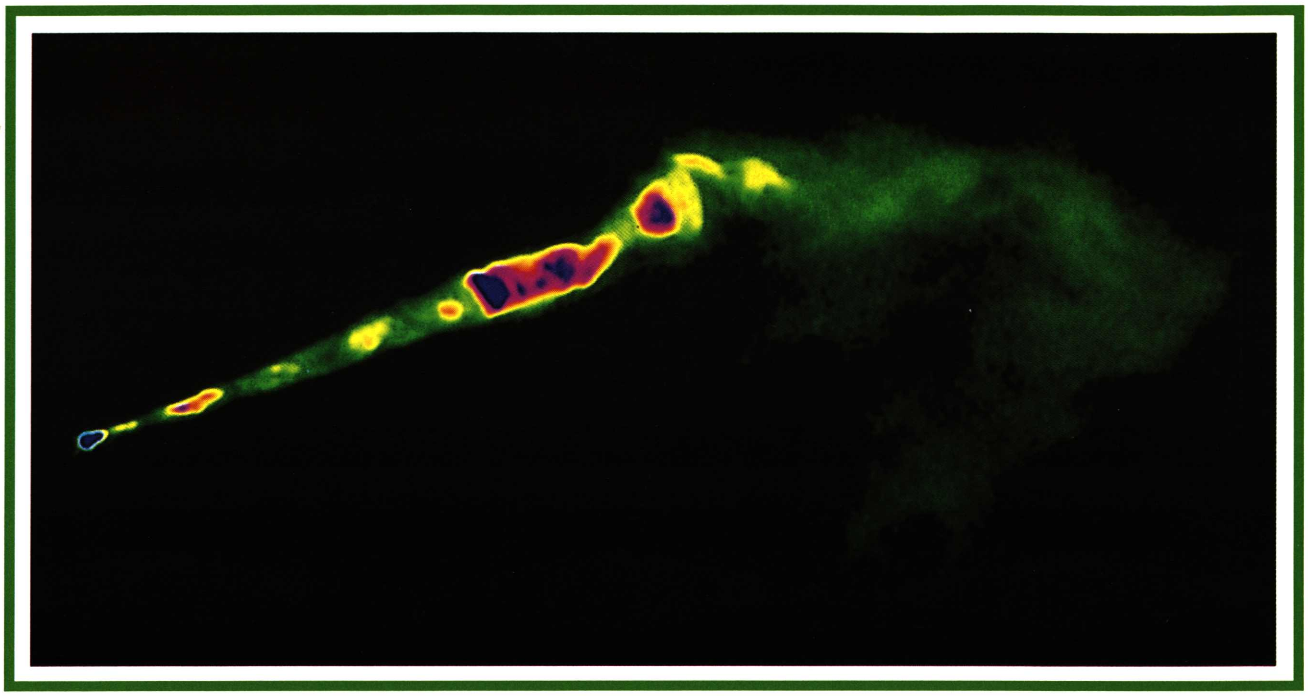


PROGRAM PLAN
1995

NATIONAL RADIO ASTRONOMY OBSERVATORY

Cover image: Radio emission from the relativistic jet in radio galaxy M87 (Virgo A). Gas flowing out of the center of the radio galaxy (the small left-most blue spot) is traced in this VLA image by its radio emission. The extent of the jet seen here is more than 7500 light-years. From repeated VLA observations made over 12 years it has been possible to see the bright radio clumps, or knots, of emission flow away from the galactic nucleus at a velocity of greater than one-half the speed of light. Observers: J. Biretta and F. Owen.

NATIONAL RADIO ASTRONOMY OBSERVATORY

CALENDAR YEAR 1995

PROVISIONAL PROGRAM PLAN

October 1, 1994

The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under Cooperative Agreement NSF/AST 9223814.

TABLE OF CONTENTS

FIGURES

I. INTRODUCTION

After more than 35 years of radio astronomy research at the NRAO, one can say with no equivocation that the radio sky is rich in its diversity, complex in its revealed physical processes, and filled with surprises. Figure 1 is a picture of the radio sources seen by the former NRAO 300 Foot Telescope superposed on the telescope site at Green Bank, WV. A casual look gives the impression that the radio sky has the same appearance as the sky at visual wavelengths, both are filled with points of light. However, a detailed comparison shows that essentially none of the bright radio sources seen here coincide with bright optical stars or nearby galaxies. The bright radio universe is parallel to the bright optical universe; the two rarely overlap. Indeed, it is precisely because the radio sky is populated by objects other than nearby stars and galaxies that we were led to the discovery of quasars, pulsars, and radio galaxies. It is these and kindred objects that are now subjects of intense study by astronomers using the NRAO Very Large Array (VLA) and Very Long Baseline Array (VLBA).

In 1995 we plan to lay the groundwork for a similar exploration of the millimeter-wave sky with design work done in preparation for construction of the Millimeter Array (MMA). At millimeter wavelengths we know that the principal emission mechanism is thermal emission — both thermal spectral-line emission from molecular clouds and thermal continuum radiation from interstellar dust, seen in galactic nuclei, protoplanets, protostars, and protogalaxies. But we have little knowledge of the objects that one can observe and study with an instrument having the unprecedented sensitivity and resolving power of the MMA. It is clear, however, that the MMA will:

- detect dust continuum emission and the molecular gas associated with the first generations of star formation in evolving galaxies at the earliest cosmological epochs;
- resolve the gaseous disks and reveal the chemistry of protostellar systems;
- unveil the elemental and isotopic products accumulated over a billion years of stellar nucleosynthesis in the expelled envelopes of dying stars.

With an improvement of more than two orders of magnitude in sensitivity and image detail over existing millimeter-wave instruments, the MMA will present us with discoveries as surprising in their way as were the discovery of quasars at radio wavelengths.

"PARALLEL UNIVERSES" - A COMPOSITE PICTURE OF THE RADIO SKY ABOVE AN OPTICAL PHOTOGRAPH OF THE GREEN BANK, WV SITE.

NRAO

NATIONAL RADIO ASTRONOMY OBSERVATORY - Operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

As a national institution, the NRAO provides an expeditious and cost-effective way for large astronomy facilities such as the MMA to be built and operated for the common benefit of the entire astronomical community. Experience at the NRAO in operating the VLA, VLBA, the 12 Meter (millimeter-wave) Telescope, and the 140 Foot Telescope has shown that the Observatory can support the individual research endeavors of a large number of users and a rich diversity of research. Each year more than 850 scientists and students make use of NRAO facilities. The scientific interests of such a large group of astronomers includes objects as near as the sun and planets and as distant as the quasars and last scattering surface of the primordial background radiation. Astronomers seek to understand how stars and galaxies form, what physical mechanism powers the quasars and radio galaxies, and the chemical signatures of planetary formation. A summary of the rich variety of research to be pursued at the NRAO in 1995 is given in Section II.

The NRAO observing facilities are described in Section III. Each instrument provides astronomers with a different probe of the astrophysical environment or phenomenon that they are investigating. Each instrument as well can have its capabilities enhanced through a considered program of instrument modernization or replacement. The specific plans to do so are present in general terms in Section III. The instrument development and computing capabilities needed to support the plans are outlined in Section IV.

Encouraging progress continues to be made on construction of the Green Bank Telescope (GBT) as noted in Section V. The antenna structure is complete up to the elevation axis. Specifications for the GBT receiving systems, as well as for the capabilities of the GBT spectrometer, have been established in consultation with prospective telescope users. Good progress on all these areas can be reported already.

Section VI is a summary of the two major new initiatives at the NRAO, the Millimeter Array and a major upgrade of the VLA instrumentation. Design studies for the MMA have been going on, at an accelerating pace, at the NRAO for more than ten years; this work is reported in Section VI. Summarized also in this section are plans to upgrade the correlator, IF, and receiving systems of the VLA. On a longer term we plan to provide three or four new antennas near Socorro to meld the longest VLA interferometer spacings smoothly into the shortest VLBA interferometer spacings, thereby creating a single, continuous array.

Sections VII and VIII describe on-going programs at the NRAO in support of the research of government agencies other than the NSF and NRAO programs specifically designed to further the educational pursuits of science students. The financial tables for 1995 are given in Section IX.

II. 1995 SCIENTIFIC PROGRAM

1. The Very Large Array

Already known as an extremely versatile instrument, the VLA expanded its capabilities in 1994, and the scientific community is well underway toward using those capabilities to make 1995 an unusually productive research year. The scientific value of the VLA continues to be demonstrated by the demand for observing time. For each hour of observing available, more than two hours are sought. The VLA has served researchers from a wide variety of specialties, and has proved particularly effective as a partner to both ground- and space-based instruments observing in other wavelength regions.

In 1995, NRAO will again devote large amounts of observing time to VLA sky surveys, conducted in both the D and B configurations. The 1.4 GHz D-array NRAO VLA Sky Survey (NVSS) will cover the sky north of $\delta = -40°$ (82% of the celestial sphere) by the end of 1996. The principal data will be (1) a set of 2326, 4° x 4° continuum map "cubes" with three planes containing Stokes I, Q, and U images plus (2) lists of discrete sources. The NVSS is being made as a service to the astronomical community, and all data produces are being released as soon as they are produced and verified.

Approximately 3 sr of sky have already been observed in the NVSS survey and the first map cubes have been released electronically. All maps have θ = 45" FWHM resolution and nearly uniform sensitivity. The rms brightness fluctuations are $\sigma \approx 0.45$ mJy beam$^{-1} \approx 0.14$ K (Stokes I) and $\sigma \approx 0.29$ mJy beam$^{-1} \approx 0.09$ K (Stokes Q and U). The rms uncertainties in right ascension and declination vary from 0".3 for strong (S >> 30 mJy) point sources to 5" for the faintest (S ≈ 2.5 mJy) detectable sources. Map production will continue throughout 1995, and at least 3 sr of sky will be observed during 1995 DnC- and D-configuration sessions. Programs to read and manipulate the FITS-format NVSS images on PCs will be developed to make the NVSS more accessible to non-professionals — amateur astronomers, teachers, students, etc.

The B-array survey, FIRST, had its initial set of observations in the summer of 1994 and sky images are being made. As with the NVSS survey, the FIRST images will be available as they are produced over the Internet. The goal of the FIRST project is to obtain precise radio positions and flux densities over a 10,000 square degree region of sky that is also being imaged at optical wavelengths as part of the Sloan sky survey. The FIRST survey will continue for the next two times that the VLA is in its B-configuration. Although the surveys have impacted the amount of observing time available to other projects, they already have produced a valuable resource for the scientific community. As the surveys continue and more data products are provided, the value of this resource will increase.

The VLA has been an instrument of proven value to planetary science since 1979. We expect both the value and the visibility of the VLA to the planetary science community to increase in 1995 because of a new Jansky Postdoctoral who is a planetary specialist. This staff addition will help NRAO to better serve planetary scientists by providing them with a point of contact more familiar with their needs and by providing an in-house voice for the planetary community as the capabilities of the instrument are evolved.

Spectral-line observations of Mars in 1995 will continue a very successful program of mapping seasonal variations of water vapor on Mars. Previous observations monitored the distribution of water vapor on the planet through three of its seasons. The new program will cover the fourth season and re-observe the other seasons to begin developing information on inter-annual variations in the planet's water-vapor distribution. This study is producing information fundamental to understanding the past and present climate of Mars. Looking farther out in the solar system, another observing project will study Saturn's ring system. High-quality VLA microwave images of the rings, made at varying inclinations of the ring system with respect to earth, are expected to help researchers to produce a detailed model of the composition and size distribution of the particles in the rings.

In December 1995, NASA's Galileo probe is scheduled to enter the atmosphere of Jupiter. The VLA will be used to receive the probe's signal during its descent, to measure the signal's Doppler shift, and thus deduce wind speed versus altitude for the Jovian atmosphere.

Planned studies of the sun will focus on a number of solar phenomena. One investigation will use VLA observations in an attempt to learn more about long-lasting, non-thermal radio sources on the sun, particularly the relationship among different types of such sources. This investigation, which also will utilize data from spacecraft, will help test models of the origin and evolution of these sources. Another study will seek to confirm a 1992 VLA observation of 3-minute oscillations in the umbra of a sunspot. This study, which will seek to refine the horizontal structure in these oscillations, can provide valuable information on the conditions in the chromosphere-corona transition region. Another study will observe the sense of polarization of sunspot radio sources as a function of frequency to learn about the temperature gradients in the solar atmosphere above active regions. In conjunction with the Yohkoh satellite, the VLA will be used to study the evolution of coronal streamers to yield new information about the stage at which these streamers erupt to form coronal mass ejections.

Similarly, the VLA will be used in a cooperative study with the Russian CORONAS satellite and the Compton Gamma Ray Observatory to investigate elementary structures in coronal energy release events and their relation to the coronal magnetic field. The VLA will provide high-time-resolution information for this study.

Stellar research at the VLA will, as usual, cover the whole life cycle from protostars to supernova remnants. The addition of 7 mm receivers to the VLA, completed in 1994, has provided a powerful tool for probing young stellar objects and their environments, and researchers are making heavy use of this capability. At the other end of the cycle, the VLA continues to be ready for rapid observation of new supernovae, as demonstrated by detection of radio flux from SN1994I within 24 hours of that supernova's discovery. Monitoring of past supernovae will continue, with the goal being to compile complete radio light curves for these objects. Gamma ray bursts are another target of opportunity that will be pursued in the coming year. The VLA will be used to seek possible transient radio sources within the error boxes of bursts within one week of the burst. If detected, such a radio source would be a particularly significant discovery because its positional accuracy would be sufficient for the source of the bursts to be identified.

Protostars and young stars will receive considerable attention from VLA observers. A study of several "Class 0" very young protostars will seek to test the hypothesis that these objects are associated with ionized mass outflow, while a detailed mapping of a single, strong Class 0 source will seek to study emission from the envelope of material falling into the object and to search for the protostellar disk. A 7 mm search of a dense molecular cloud will seek to find embedded protostars. Another molecular-cloud observation program will seek to use NH_3 maps to study the shock front excited by bipolar outflows and to search for pre-protostellar clumps. Observations at 7 mm and 1.3 cm will seek to image dusty disks presumed to surround young stars. A young stellar object, still embedded in hot dust, that has shown a large radio flux density increase will be monitored to provide information that, along with infrared data, will help to determine the mechanism responsible for the flare.

Moving to slightly older objects, a study of T Tauri stars will use the VLA's 7 mm capability to attempt characterization of the size and radial structure of protoplanetary disks around them. A survey of optically selected double Herbig-Haro objects will seek to reveal information about the location of their energy sources and whether the double objects are parts of single outflows or are independently powered. A continuum survey of recently discovered Herbig-Haro objects will seek to reveal the central outflow source by tracing the outflow's brighter knots.

The VLA will be part of a multiwavelength campaign, including the Hubble Space Telescope (HST) and the Extreme Ultraviolet Explorer (EUVE), to study an active flare star. Other observations will study a close binary system consisting of a white dwarf and a red dwarf, also in conjunction with EUVE. These studies will seek to correlate or distinguish radio flare phenomena with flare activity observed at other wavelengths.

A long-term program of timing fast pulsars at the VLA, begun in 1990, already has produced significant results, and will be continued. This program will continue observations of a triple pulsar system and an eclipsing binary system, and to measure apsidal advance (and thus mass) of binary pulsars. These ongoing studies will produce new information about the individual systems as well as more general information about pulsars and their environments.

Supernova remnants (SNRs) will receive significant attention from VLA researchers in the coming year. An old favorite, Cassiopeia A, will be the target of studies to continue the detailed archive of data on this complex object. In addition, the new observations of Cas A will seek to begin studies of its magnetic field evolution, to distinguish between stellar and interstellar origins for its dense clumps, and search for temporal variations in its spectral index. A four-configuration study of Tycho's SNR will compare the small-scale structure in the shell with previous VLA observations from 1983-1984, to detect temporal changes. This study will yield clues about the kinematics of the shock fronts, interactions with the surrounding medium, and the evolutionary state of the SNR. Four other SNRs within the Galaxy will be imaged at high sensitivity and resolution in a study aimed at producing important information on the physics of electron acceleration in SNRs. The study of SNRs will extend beyond the Galaxy to M31, where VLA observations of large-diameter SNRs in that galaxy will provide valuable information about SNR evolution. Finally, a survey of SNRs in nine other nearby galaxies will shed additional light on SNR evolution and potentially on the role SNRs play in the regulation and production of cosmic rays.

The physics of supernovae is poorly known. Especially uncertain is (1) the late stage of evolution of the supernova progenitor star immediately prior to the supernova event itself, and (2) the evolution of the neutron star remnant following the explosion. In 1994 a unique event was observed with the VLA which almost certainly involved a collapsed star, perhaps the remains of a star that experienced a supernova explosion in the recent past. Known as a variable source of hard x-ray emission, the object GRS 1915+105 was observed to experience a rapid increase in its radio flux density. Subsequent VLA images show that this resulted from the simultaneous ejection of two clumps of oppositely directed relativistic particles. The clumps were observed to separate at 92 percent of the speed of light. The enormous energy involved in the process, 10^8 L_o, and the relativistic structure of the emission process provides for the first time a framework within which a model of the x-ray emission may be constructed.

The time series of VLA images of GRS 1915+105 is shown in Figure 2. This figure appeared on the cover of Nature September 1, 1994. Further work on this and other radio/x-ray sources will occur in 1995.

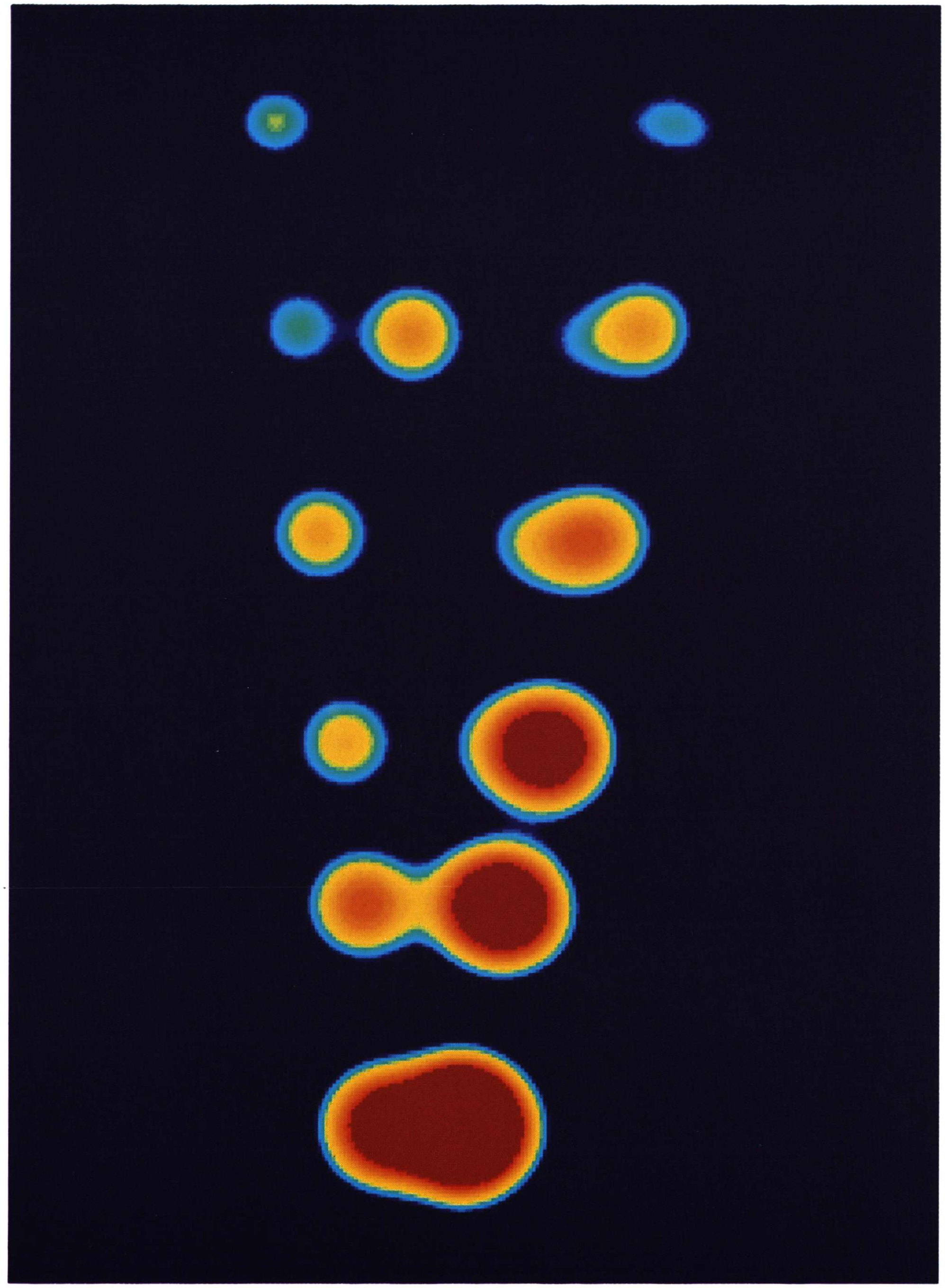
VLA studies of the interstellar medium (ISM) will focus on a number of questions. A search for long carbon-chain molecules will seek to determine if these may be the cause of the long observed, diffuse, interstellar bands of absorption. A study of CS emission toward a contracting molecular cloud core will yield information on the kinematics of the gas to help in detecting infall toward young stars. Researchers will look for a CS absorption line at 49 GHz to measure the molecular content at Galactic radii far beyond the solar circle to provide information on the formation and evolution of our Galaxy and to learn if cold molecular gas may constitute some portion of the dark matter required to account for observed galactic rotation curves.

Researchers will make high-resolution observations of ammonia as a means of learning more about the environment in which water masers form. A multiconfiguration study of the CH_3OH maser region in the Orion Nebula will measure the size of the masers and allow determination of their coherence length, thus providing data for detailed modeling of the physical parameters of the masing region.

In a number of studies, radio recombination lines will be used to probe H II regions. These studies will seek to test models for the kinematics and morphology of the H II regions and to determine their detailed spatial and velocity structures.

The study of galaxies in all their variety and complexity is a mainstay of research at the VLA. This starts, appropriately, with studies of our own Galaxy, and planned observations include detailed study of a recently discovered radio counterpart to a black hole candidate near the Galactic center.

Moving past the Milky Way, a study of dwarf galaxies in the Local Group will seek to learn more about the distribution of cold and warm atomic phases of the interstellar medium in those galaxies and the relationship of structure in those phases to the star-formation rate. An investigation using both the VLA and Kuiper Airborne Observatory will study nearby spiral galaxies and attempt to learn if far-infrared luminosity of galaxies is an indicator of current star-formation rate. A pair of interacting galaxies will be observed in detail to study the gas dynamics and the evolution of star formation during the interaction. Ring galaxies, believed to be the result of collisions, will be studied by at least two teams of investigators to learn



SUCCESSIVE WEEKLY VERY LARGE ARRAY (VLA) IMAGES
OF GRS 1915+105 IN APRIL 1994

NATIONAL RADIO ASTRONOMY OBSERVATORY - Operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

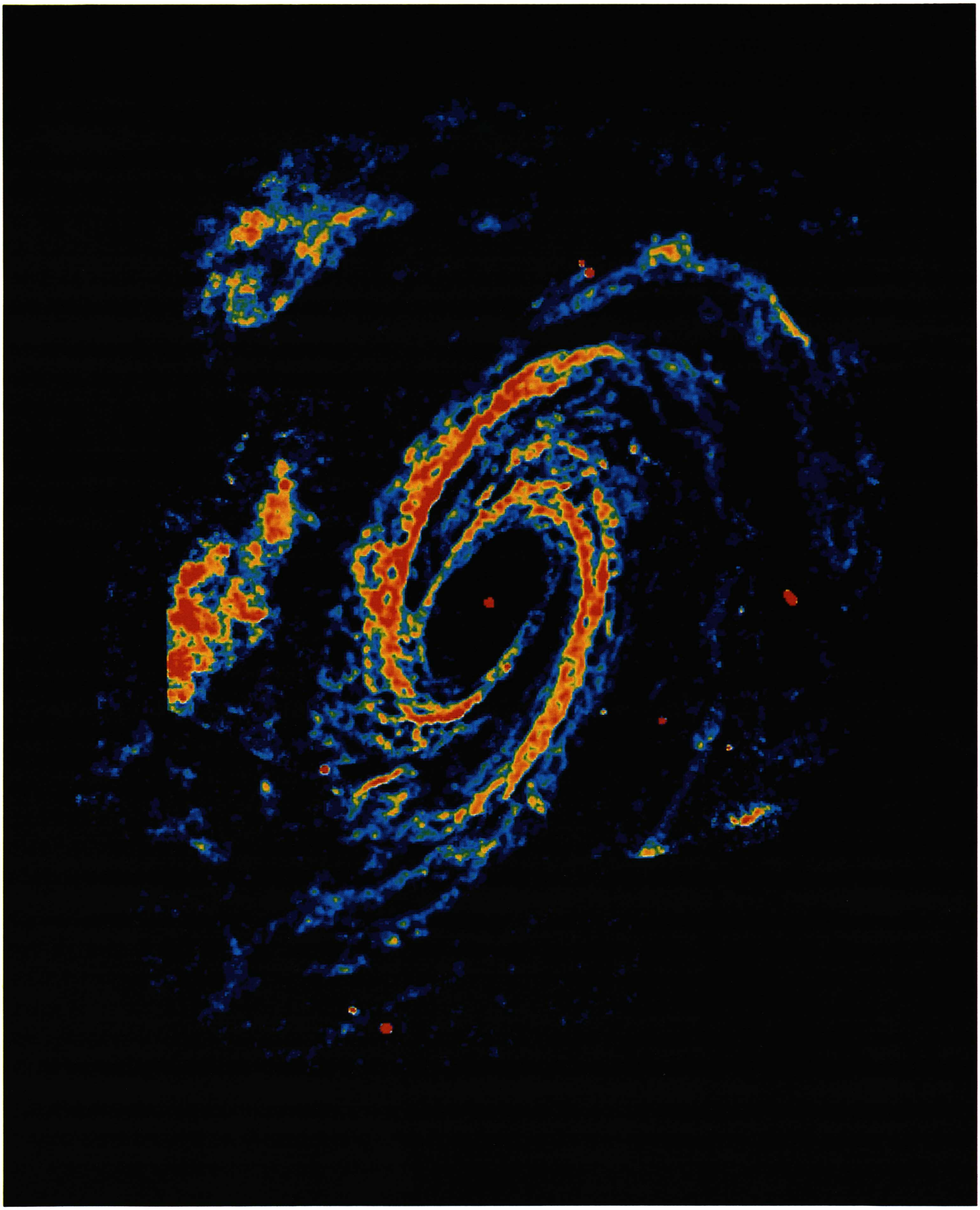
more about the current structure and evolutionary history of such systems. A sample of low surface brightness galaxies will be observed to determine if low and high surface brightness galaxies show the same correlations between radio emission and emission at other wavelengths.

Observations of neutral hydrogen at 21 cm continue to represent an extremely powerful tool for investigating the structure and dynamics of galaxies, and this tool will be used often in the coming year. Studies of neutral hydrogen will provide new rotation curves and thus data about the mass distribution of galaxies, new information on the formation of shells around galaxies, and potentially may discover additional neutral-hydrogen companions to blue compact galaxies. Following particularly successful mapping of HI in M81 (shown in Figure 3), a multiconfiguration project similarly will map M33 in great detail. Among the types of galaxies to be probed in detail by VLA HI observations are: polar-ring galaxies, barred Magellanic galaxies, barred spirals, flocculent galaxies, nearby Seyferts, ultraluminous far-infrared galaxies, and galaxies with extreme mass-to-luminosity ratios.

Neutral-hydrogen observations also will be used to study a spiral galaxy being cannibalized by a giant elliptical near the center of a cluster, gas condensations near an interacting pair of galaxies, pairs and groups of galaxies with common HI envelopes, and galaxies within a rich cluster.

A number of investigators will use the VLA to study the magnetic fields of galaxies and clusters of galaxies. These studies will provide new information on the structures of such magnetic fields, their relationship to interstellar gas, the possible connection of "tangled" magnetic fields and gas clouds, and the origins of the cluster magnetic fields. Galactic radio halos will be studied to determine their extent, to learn about their filamentary structure, and their connection to star-forming regions in the disk.

Several studies will seek to yield new information on radio galaxies. High-resolution, high-sensitivity observations of the jets of nearby FR-I galaxies should provide direct constraints on models for the physics of energy transport in these systems. A study of the ends of FR-I jets will seek to distinguish between competing models for the flows in the jets. The hypothesis that jets in FR-I sources begin at relativistic velocities and slow down on kiloparsec scales will be tested by detailed observations of the base of the jets and of the magnetic field structure of one such source. FR-II radio galaxies also will be studied to provide crucial evidence for testing models of the origin of their jets. VLA imaging of radio galaxies at intermediate redshift will seek to complete a sample aimed at finding objects intermediate between the FR-I and FR-II sources, and produce information about possible



VERY LARGE ARRAY (VLA) IMAGE OF NEUTRAL HYDROGEN IN THE GALAXY M81 (NGC 3031)

NATIONAL RADIO ASTRONOMY OBSERVATORY - Operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation

changes in the environment of powerful radio galaxies over time that might account for the production of the different types.

A program to study larger-scale structure of radio galaxies at redshifts between 0.6 cm and 1.8 cm, combined with HST images of the same galaxies, will seek new information on evolutionary effects at this redshift range. Moving farther outward, observations at 1.3 cm will seek to map CO in a radio galaxy at z = 3.6 and to estimate the molecular content of the most distant known galaxy, at z = 3.8.

Researchers seeking new gravitational lens systems will use the VLA to make rapid images of a large number of the radio lobes of radio galaxies and quasars. Other workers, who have observed the Sunyaev-Zeldovich effect in a sample of galaxy clusters using the 5.5-meter telescope at the Owens Valley Radio Observatory (OVRO), will use the VLA to map the discrete sources within those clusters. Another group, observing the same effect with the Ryle Telescope, also will use the VLA to refine the structure within the clusters. Both of these groups hope, with further work, to use the Sunyaev-Zeldovich effect to arrive at improved values for H_o.

2. The Very Long Baseline Array

Early results from the VLBA hint at the wide range of exciting programs planned for the next year. Of particular interest to extragalactic astronomers will be observations intended to examine the popular models which attempt to unify radio galaxies, quasars, and AGN through their orientation with respect to the observer. Anisotropic emission is thought to arise as a result of relativistic motions which produces highly focussed emission and partial obscuration by a dusty molecular torus.

The VLBA will be used to study the relativistic motion in a sample of about a hundred objects with high resolution and good image quality in order to determine the dynamics of the ejection of relativistic plasma and to better understand how the radio jets, which sometime extend for hundreds of kiloparsecs away from the central engine, are focused and collimated within regions less than a few parsecs across.

The first observational evidence of the postulated dust torus was recently reported from some of the first observations made with the VLBA. Observations of the nearby radio galaxy NGC 1275 (3C 84) show a counterjet which is strong only at short wavelengths, apparently due to absorption of the radio emission at longer wavelengths by the surrounding dust. Planned multi-epoch and multi-wavelength observations with the VLBA will determine more

VERY LONG BASELINE ARRAY (VLBA) IMAGE OF 3C84, WITH JET AND COUNTERJET

NATIONAL RADIO ASTRONOMY OBSERVATORY - Operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

accurately the spectrum of the jet and counterjet as well as their relative motions. This will verify the absorption hypothesis and allow a unique determination of the true velocity of the relativistic ejecta.

The VLBA will also be used to survey much larger numbers of radio sources than previously possible to classify their radio morphology, to detect new superluminal sources, to find potential very compact sources to study with the upcoming series of space-ground very long baseline interferometry (VLBI) missions, and to search for candidate gravitational lenses, especially so called micro-lensing which produces lensed images separated by only a few hundredths of an arc second, beyond the resolution limit of any other astronomical instrument. Detection of micro-lensing would support the existence of dark matter postulated to exist in the form of intergalactic massive objects of the order of a million solar masses. Studies of individual gravitational lens systems will provide tight constraints on lensing models, and by regular observations of the differential time delay of observed intensity changes in the twin images, observers hope to obtain an independent determination of the Hubble constant.

The VLBI surveys of source structure and motions will also be used for a variety of cosmological studies. Determination of the angular size — redshift and angular velocity — redshift relations may give new estimates of the mass density of the Universe, free of any evolutionary effects of the standard measuring rod. Especially exciting are the prospects for making an independent determination of the Hubble constant. VLBA observations will be used to verify a previous marginal detection of a counterjet in the powerful extended radio galaxy Cygnus A and to refine the measurement of apparent motion of the jet component. The planned observations of the jet and counterjet motions will give uniquely the true value of the space velocity and orientation, which when combined with the apparent angular velocities and redshift will give an unambiguous determination of the elusive Hubble constant, as well as direct confirmation of the widely assumed two-sided relativistic jet model.

A systematic study of the of the nuclei of low luminosity FR-I radio galaxies already begun will continue with the VLBA with special emphasis on the nearby low luminosity sources in M82, M84, M87, M101, and NGC 5128. The aim of this project is to compare the morphology and dynamics of FR-I radio galaxies with their more powerful FR II, quasar, and BL Lac counterparts in an attempt to understand the relationship among these apparently widely disparate phenomena which range in luminosity over a factor of more than a million.

High-resolution imaging will be enhanced by the polarimetric capability of the VLBA which give new insight into the orientation and distribution of magnetic fields near the central engines of quasars and AGN. Polarization images will give unambiguous support to lensing models.

Within our own galaxy the VLBA will observe the continuum emission from the very compact source at the Galactic center, in order to better determine its structure as well as OH masers around OH/IR stars in the Galactic Center region. These observations will be used to examine the intervening plasma which broadens the image even at short millimeter wavelengths. Observations of OH, CH_3OH, H_20, and SiO masers will address issues regarding the physical conditions in the maser regions and detailed questions of maser physics. During the past year VLBA observations of the SN 1993J and SN 1994I has received considerable attention, and this work will continue during the next year. The versatility and flexibility of the VLBA will be exploited to pursue other targets of opportunity, such as the recent x-ray nova in Scorpius.

One of the most important problems in contemporary geophysics is the rigidity of tectonic plates. Geodetic observations with the VLBA will study the stability of the North American plate and the relative motions of the North American and Pacific plates using the trans-Pacific baselines to the VLBA antenna in Hawaii. Repeatabilities of several millimeters have already been obtained, and it is hoped to extend this to one millimeter on baselines of nearly 10,000 kilometers. Geodetic data obtained with the VLBA is made available to the scientific community for study and analysis as soon as it is processed.

For some of these studies, observers will supplement the VLBA by including the Green Bank 140 Foot Telescope, one or more VLA antennas, as well as a number of foreign antennas to enhance the sensitivity and dynamic range of the images.

3. 12 Meter Telescope

The 12 Meter Telescope is now equipped with sensitive, dual-channel SIS receivers covering all the primary wavebands of the telescope from 68 to 300 GHz. The sensitivity and flexibility of these systems allow observers to attack the most challenging and topical problems confronting millimeter-wave astronomy today. Enhancements to these systems are planned in the coming year, including a doubling of the receiver bandwidth, that will allow observers to pursue an even wider range of programs. Astronomers most often use these dual-polarization, single-beam receivers to achieve the utmost sensitivity toward a single point on the sky, or perhaps to map a limited region. Some of the most fundamental, ground-breaking discoveries of recent years, such as the detection of molecular gas in high-redshift galaxies and the discovery of new, interstellar molecules, have been made with these systems.

Another class of problem-oriented research requires the ability to rapidly image large fields. Many such problems concern the structure of external galaxies and the large-scale structure of molecular clouds and star-forming regions in the Milky Way. The 12 Meter now has powerful tools for rapid imaging. The new on-the-fly observing mode, a highly efficient observing technique, can be used with any of the single-beam receivers in either spectral line or continuum modes. This technique is made possible by a marriage of the powerful and flexible on-line computer systems and the high-sensitivity receivers at the 12 Meter. In addition, the 8-feed, 230 GHz receiver nears completion and should be available in 1995 for rapid imaging in the 1.3 mm wavelength band. A next-generation, 32-feed receiver is being planned.

A considerable emphasis of 12 Meter research in the coming year will concern external galaxies. Several groups are pursuing detections of molecular emission in high-redshift galaxies. Very recently, the 12 Meter has been used to detect CO emission in a galaxy with a redshift $z > 3$. Such redshifts correspond to the first 1-2 billion years of the universe. Molecular detections help to confirm models of stellar processing and heavy element production in the early universe.

Other upcoming research on external galaxies seeks to understand the morphology of specific types of galaxies. For example, one program will try to locate the molecular gas in early-type (Sa) spiral galaxies. There is a dilemma in that molecular gas appears to be centrally confined in such objects and has not, heretofore, been detected in regions of star formation. The researchers will try to confirm evidence that there may, in fact, be a ring of molecular gas in the star-forming regions. Another program seeks to understand the relationship between the type of Seyfert activity and the characteristics of the host galaxy. Yet another program will test the hypothesis that dwarf elliptical galaxies evolve from blue-compact-dwarf galaxies. Several projects will use the new on-the-fly, rapid imaging system to make large-scale, high-sensitivity images of CO emission in such galaxies as M83 and IC 342.

Astrochemistry has long been a specialty of the 12 Meter. Over the years, the facility has accounted for a substantial majority of the detections of interstellar and circumstellar molecular species. This trend continues: in the past year the 12 Meter produced detections of six new species. About 100 species are now known. Most of the species searches are oriented toward solving a specific problem in astrochemistry. For example, two projects involve searches for silicon-bearing species and seek to answer the question of whether extraterrestrial silicon chemistry can approach the complexity of carbon chemistry. Another project aims to detect a rare aluminum isotope in a circumstellar environment; this study will provide an important constraint for theories of stellar nucleosynthesis.

Some of the studies in astrochemistry utilize known species to understand different physical environments. For example, one upcoming project will search for emission features of HCO+, HCN, C_3H_2, and other species in diffuse clouds. Using both emission and absorption features detected with millimeter-wave interferometry, the researchers are finding a rich and previously unidentified chemistry toward diffuse clouds.

In the coming year, astronomers will also be using molecular-line emission as a tracer and diagnostic of several molecular cloud and star-formation regions. One project is using two rotational transitions of HCO+ and one transition of its deuterium isotope (DCO+) to analyze a stellar outflow wind in the Taurus region. The excitation properties of the different species will identify which material is flowing out from the star itself and which is swept up ambient material. Another project will use the on-the-fly mapping technique to study the physical conditions of molecular material and the material's interaction with young stars in the Serpens region.

In the last year, the 12 Meter staff developed a polarimeter for use with the 3 mm receiver. Both linear and circular polarimetry are possible. Initial results indicate that it is possible to measure polarization at levels of one percent or less. Astronomers intend to use this device to search for Zeeman splitting in selected molecular lines. The results will be used to measure the strength of the magnetic fields in molecular clouds, a critical parameter to the star-formation process. Another polarimetry project will search for linear polarization in diffuse interstellar clouds. If detected, the result can be used to measure the orientation of the magnetic field lines.

The 12 Meter expects to participate in millimeter-wave VLBI during the coming year. Kitt Peak provides essential baselines for most experiments, and the sensitivity of the 12 Meter makes it critical to the success of many VLBI experiments. In the past year, the 12 Meter was used with the OVRO and Haystack observatories to measure the size of the emission source at the galactic center. This year, the 12 Meter will be used to study active galactic nuclei. With a global network, millimeter-wave VLBI can achieve resolutions of 50 micro-arcseconds. The 12 Meter is now linked to the Kitt Peak VLBA station and makes use of VLBA time standard and data recorders.

Finally, one group will be performing an important study of the earth's atmosphere and the atmosphere of Mars and Venus. The earth project will study the diurnal variations of ozone and other species in the upper stratosphere and mesosphere. Venus will be measured near its inferior conjunction and a global dust storm on Mars, first detected last spring with the 12 Meter, will continue to be followed.

4. 140 Foot Telescope

The 140 Foot Telescope is in continued demand because of its excellent receivers, versatile detectors, and good sky coverage. Observations in 1995 will span the frequency range from 350 MHz to 35 GHz. The existence of the National Radio Quiet Zone surrounding Green Bank allows observations to be made at frequencies that are rendered unusable at other observatories.

A significant fraction of the observing time in the coming year will be devoted to pulsars. There are several major searches for new pulsars now underway which will continue into 1995. One is an all-sky survey for new millisecond pulsars. Millisecond period pulsars can be used as precise timing standards for a number of purposes, so any addition to their numbers is welcome. Other surveys search for pulsars toward gamma ray or radio sources. There are now five active observing programs that use the 140 Foot Telescope to measure pulse arrival times for selected pulsars every month or two. Two of these programs have been in operation for four years and are now yielding useful data on pulsar periods and their variation. Other projects target specific pulsars suspected of having a companion, of being accelerated by the varying gravitational potential of a globular cluster, or of having internal structural changes to the neutron star that affect its period. Pulsar monitoring can also reveal changes in the interstellar medium which modulates the pulse arrival time and pulse shape. These data give information about the ionized component of the interstellar medium on angular scales that are inaccessible to other measurements. Pulsar monitoring will be an important use of the telescope in 1995.

The telescope will also be used to search for radio counterparts to the enigmatic gamma-ray bursters. Periodically, observers will map the radio sky around the location of recent gamma-ray burst events in the hope of turning up a radio source that is part of the phenomenon. This project requires a highly sensitive multi-beam receiver and access to the telescope at regular intervals.

Interstellar chemistry is now a rich field, and the 140 Foot Telescope in 1995 will be used for projects as diverse as a search for long-chain carbon molecules in various astrophysical environments, measurement of CH at cloud boundaries where there is a transition between molecular and atomic states of interstellar gas, and monitoring of H_2O emission from star-forming regions. Recent spectral surveys with the 140 Foot have turned up more than 100 unidentified lines in a single source, and follow-up observations to untangle the spectroscopic evidence are planned for 1995. Studies of OH emission from evolved stars will determine the kinematics and distribution of these objects.

Molecular studies are important not only for our Galaxy, but for the understanding of the chemical evolution and galaxy-formation process in the early universe. Recently two transitions of the CO molecule were observed with the 140 Foot from an object at a redshift $z > 3$. This finding implies that large concentrations of molecular gas were present in the early universe. The broad frequency coverage of the front-ends and back-ends of the 140 Foot make it suited for these kinds of studies, more of which will be undertaken in 1995. This area promises to be one of exceptional interest and reward in the next few years.

There will also be searches for extragalactic HI lines at large redshift in 1995. The 140 Foot Telescope is uniquely suited for these observations because of the relatively low level of interference at the Green Bank site. Searches for the HI line at frequencies below 1 GHz will be made toward gravitational lenses and damped Lyman-alpha systems.

The telescope is in demand for observation of nearby galaxies in the HI line. The question of the relative mass of gas and stars in galaxies is an important one, and the telescope will be used to make accurate measurements of the total HI flux of selected galaxies. These data will be used to complement interferometric observations which might not detect all the extended HI flux. The most nearby galaxy, the Milky Way, will also be studied in the HI line in 1995. Projects to determine the faintest end of the high-velocity cloud luminosity function give information on possible infall of gas into the Galaxy and on star formation far from the galactic plane. By mapping specific interstellar HI clouds, it should be possible to understand recent observations of dark patches in the soft x-ray background. The HI clouds are expected to absorb soft x-rays, so there should be a detailed anticorrelation between the amount of distant x-ray emission and the amount of foreground HI emission. Measurement of an accurate total HI column density toward quasars and active galactic nuclei allows ultraviolet measurements of these objects to be corrected for galactic reddening and x-ray measurements to be corrected for absorption. There will be very precise measurements of the magnetic field in interstellar clouds though observations of the Zeeman splitting of the HI line at 21 cm. The

Zeeman effect will also be studied in interstellar molecular clouds through observation of the OH lines.

The crash of Comet Schoemaker-Levy into the planet Jupiter was observed with the 140 Foot Telescope at 1400 MHz during the summer of 1994, and the planet will continue to be monitored throughout 1995 to see if the impact has any long-term effects on its radio emission.

About 20 percent of the observing time at the 140 Foot Telescope in 1995 is expected to be devoted to VLBI. The telescope is in demand for observations that require the sensitivity that the relatively large aperture gives, and its geographic location is important in providing baselines between the large European and the western American telescopes.

III. USER FACILITIES

1. Very Large Array

Present Status

More than 625 scientists used the VLA for their research work in 1994, and a similar or larger number will do so in 1995. Demand for the VLA arises both from the multi-wavelength nature of contemporary astronomical research and from the flexibility of the telescope. With regard to the former, it is now widely recognized that radio observations provide unique insight into a variety of astronomical objects that may be used to complement the information gained with telescopes operating at visible, infrared, gamma-ray, or x-ray wavelengths. Radio observations also may be the focus of research with complementary data provided from observations at other wavelengths. For either case, the fact that the angular resolution and field of view of the VLA is nearly identical or better than that achievable with modern detectors at other wavelengths means that all the data can be merged with no ambiguity. This is the capability astronomers need for their research.

Present Instrumentation

The VLA consists of twenty-seven, 25-meter antennas arranged in a wye configuration, with nine antennas on each 13-mile arm of the wye. The antennas are transportable along double rail track and may be positioned at any of 72 possible stations. In practice, the antennas are rotated among four standard configurations which provide a maximum baseline along each arm of 0.59, 1.95, 6.39, and 21.0 km. Reconfigurability provides the VLA with variable resolution at fixed frequency or fixed resolution at variable frequency.

The VLA supports eight frequency bands, remotely selectable; the six upper bands by means of subreflector rotation. The table below summarizes the parameters of the VLA receiver system.

The VLA receives two intermediate frequencies (IFs), each with full polarization capability in all continuum and spectroscopic bandwidths ranging from 50 MHz to 195 kHz. Within certain total bandwidth limitations, 512-channel spectroscopy is supported in all bands.

Future Plans — Electronics

When the VLA went into operation in 1980, it gave an improvement in resolution, sensitivity, speed, and image quality of more than two orders of magnitude over existing arrays. Since that time, the VLA has been an extraordinarily productive scientific instrument. However, as a result of technological advances during the past decade, new instrumentation is needed to keep the VLA at its current leading position among the world's radio astronomy facilities.

Table I. VLA Receiving System

Frequency (GHz)			T_{sys} (K)	Amplifier
0.070	-	0.075	1000[1]	Bi-Polar Transistors
0.308	-	0.343	150	GaAsFET
1.34	-	1.73	35	Cryogenic HFET
4.5	-	5.0	60	Cryogenic HFET
8.0	-	8.8	35	Cryogenic HFET
14.4	-	15.4	110	Cryogenic GaAsFET
22.0	-	24.0	180	Cryogenic HFET
40.0	-	50.0	95[2]	Cryogenic HFET

[1] Eight antennas equipped; T_{sys} includes galactic background.
[2] Ten antennas equipped.

A program to upgrade the VLA is described as a Major New Initiative in Section VI of this Preliminary Program Plan. It amounts to a major overhaul of the entire VLA electronics system.

In a sense, the upgrade is already slowly underway in the form of yearly improvements to the electronics. The installation of new 1.4 GHz receivers was completed in 1993, and ten of the VLA antennas are now equipped with 43 GHz receivers.

Two projects to reduce radio frequency interference will be completed in 1994 and 1995. These involve changes in the 21 cm local oscillator (LO) system and installation of shields on the antenna B-racks. Such incremental improvements will go on until funds for the major upgrade become available.

VLA - Repair and Maintenance

The maintenance of the VLA infrastructure continues at a high level but with a slowly changing emphasis. The replacement of the high-voltage underground power cable, which was begun in 1987, was completed in 1994. The acquisition of new and surplus heavy construction equipment has been very successful and the priority for the next few years will be on replacing the older rail vehicles. The long-term projects of rail maintenance and man-hole replacement continue, and a new major program of antenna painting was begun in 1994.

Rail system maintenance continues as a routine but highly important task. In 1994 most effort will be put into track and intersection leveling and aligning the rail spur lines that go to the antenna stations; tie replacement will have less emphasis. In 1995, these priorities will probably be reversed.

The aging of the VLA is clearly seen in the rust and staining on a large number of the VLA antennas. A program for painting the VLA antennas was initiated in 1993 to attack these problems before mechanical deterioration set in. Various systems of surface preparation and painting were investigated and some test coatings applied. In 1994 four antennas will be completely repainted and several more will have their quadrupods recoated. This work is performed by a four-man NRAO summer crew. It will take at least five years to address the current problem, and after that, antenna painting will become a regular maintenance item.

In 1991 the azimuth bearing in Antenna 21 failed, putting the antenna out of service for almost a year while repairs were made. A program is now underway to monitor the metal content of the bearing grease and the vertical play of the azimuth bearings. Although none appear in immediate danger of mechanical failure, a few antennas do show signs of progressive bearing deterioration. The azimuth bearing of Antenna 9 was replaced in August 1994 as part of its regular overhaul. As improved high-frequency receivers are put on the VLA, we will eventually need to upgrade both the reflector surface accuracy and replace more worn bearings to get acceptable pointing accuracy.

Much of the VLA outdoor maintenance is done during the summer months with the longer days and moderate weather. During this period, the regular NRAO staff is augmented by seasonal employees, and the VLA maintenance staff goes to a ten-hour workday. Eighteen temporary summer employees were hired in 1994 which allowed us to field a ten-person rail crew plus cable, manhole, and paint crews. Similar temporary staffing probably will be used in 1995.

2. Upgrade of the VLA

When designed in the mid-1970s, the VLA used state-of-the-art technology. Over the last fifteen years, however, there have been major advances in receiver sensitivity, correlator design, and the transmission of broadband signals which already have been incorporated into other, new radio telescopes such as the VLBA, the Australia Telescope National Facility, and the Nobeyama millimeter interferometer. In its current configuration, the VLA can still observe radio sources which are two orders of magnitude fainter than have been observed by any other radio telescope. By using modern, low-noise radiometers, fiber-optics transmission lines, and a broad bandwidth correlator, it will be possible to gain *another* order of magnitude improvement in sensitivity plus extend the spectral coverage of the VLA.

The VLA upgrade as presently conceived has three key elements:

- Replace most of the VLA receivers to achieve lower noise temperatures and much wider bandwidths and add two new observing bands. These receivers will provide at least 1 GHz of IF bandwidth in each polarization. This is a factor of ten increase over the 100 MHz per polarization now available on the VLA.
- Replace the buried waveguide with a fiber optics system to send the wide bandwidth signals to the correlator.
- Construct a new VLA correlator to both process the wide bandwidth signals for continuum observations and provide improved resolution and flexibility for spectral line work.

Receiver and Antenna Improvements

At the antennas, the upgrade involves improving receivers for the current observing bands, adding new observing bands, and modifying the antenna structure for improved operation. Table II shows a possible restructuring of the VLA high-frequency observing bands.

Improved Low Noise Receivers

A slow 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 ten antennas operating at 45 GHz. These receivers will remain with perhaps only minor modification. The greatest improvement in system temperature can be made at 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. Installation of such receivers will reduce the system temperature by half.

The new receivers will provide at least 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, such as methanol, that were 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 20 cm feed may 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.

New Observing Bands

Two new receiver systems for the 2.5 GHz and 33 GHz bands will be added at the Cassegrain focus. These will open new molecular line observations to the VLA, improve rotation measure studies, and permit the VLA to participate in bistatic planetary radar observations with the Arecibo Observatory.

Antenna Modifications

Adding the two new observing bands will require rearranging the feeds on the VLA feed ring and installing a new feed enclosure. Since the high-frequency receivers will be mounted very close to the Cassegrain focus, a structure more like the VLBA feed cone will probably be needed.

When 45 GHz receivers were first installed on the VLA, the ten antennas with the best surface accuracy were chosen to get these receivers. The VLA upgrade proposes putting 45 GHz on the remaining 18 antennas. This will require some effort to improve the performance of the worst antennas.

Prime Focus Receivers

Upgrades to the low-frequency performance can generally be done with relatively little cost. Ideas being discussed include adding a 600 MHz to the 327 MHz system already at the prime focus or constructing a broadband 150 MHz to 600 MHz system. A major project of placing a 800-1200 MHz prime focus system on the VLA also is being investigated. This would require extensive mechanical alterations to the antenna quadrupod and the focus/rotation mount.

New LO/IF Transmission System

In order to transmit 2 GHz of IF bandwidth from each antenna, this proposal includes a fiber-optics link to all of the VLA stations, and is expandable to include links to the nearby VLBA antennas and possible new antennas intermediate between the VLA and present VLBA stations. Separate fibers will carry the LO reference signal and the wideband IF signal. Between four and six single-mode fibers will run to each antenna station. Although low temperature coefficient fiber will be used on runs exposed to ambient temperature, a round-trip phase correction system will probably be needed.

It is not yet decided whether to send the IF back as a digital signal that is generated by samplers located at the antennas or to send an analog signal to the central electronics room.

New Correlator

The current VLA correlator is limited to a bandwidth of 4 x 50 MHz. A new correlator is needed to process the 2 GHz of bandwidth and to achieve the increase in sensitivity. Moreover, the current correlator limits the type of science which can be done due to its limited spectral resolution at wide bandwidths. At 50 MHz bandwidth, the VLA can only produce eight spectral channels. Wide-field imaging at low frequency and spectral line searches for redshifted hydrogen are inefficient with the current correlator. The specifications for the new correlator are still under discussion.

The new correlator should be capable of processing data from 32 antennas. These could be some combination of the twenty-seven VLA antennas plus the two nearby VLBA antennas (Pie Town and Los Alamos), plus up to four new antennas intermediate between the VLA and nearby VLBA stations.

Radio Frequency Interference

The desire to upgrade the VLA to wide-bandwidth performance (of order a gigahertz per polarization channel) means that the instrument will often operate outside of the protected frequency bands. The array will therefore be susceptible to radio frequency interference (RFI) to an even higher degree than it is now, especially at frequencies below 5 GHz.

While the use of independently tunable IF channels will allow users to "steer around" some of the more damaging sources of interference (e.g., airport radar, satellite signals, etc.), it is impossible to avoid all sources of RFI (e.g., aircraft transponders, mobile communications). It is therefore highly likely that all observing will be done in spectral-line mode, at least at low frequencies, to allow the identification and excision of RFI from the data in both the temporal and spectral domains. To do so will require short integrations and enhanced data handling capability.

A Robust Total Power System

A fast and accurate means of measuring the total power is needed. In recent years, the mosaicing technique has been employed with increasing frequency and success at the VLA to map large fields of view. However, to measure the visibilities for the smallest *uv's* required in most mosaiced images requires total power measurements with single antennas. These could be made with the VLA antennas by scanning rapidly across the region being mapped and adding the "single-dish" map to the imaging process. This capability requires on-line and off-line software and a stable total power system for each antenna.

Multiband Performance

For some experiments, support of multiband performance is highly desirable. For example, transient phenomena on the sun and stars would benefit greatly from simultaneous measurements in two or more bands. One possibility is to support dual-frequency measurements in the S and X bands and/or dual-frequency measurements in the C and KU bands. An additional benefit of dual-frequency observing is that one of the two bands in a given pair could be corrected for the long-standing problem of beam polarization squint through the use of a tertiary mirror.

A practical benefit of dual-frequency observing is that the lower frequency of a given pair can be used to track the phase variation of the atmosphere from which corrections can be derived and transferred to the high frequency. Implementation of such a scheme will be considered for enhanced high-frequency performance at the VLA.

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. The solution to this problem is to move the outermost VLA antennas from the D array closer to the array center and create a new, more compact array with a characteristic maximum baseline of 300 meters. About nine new stations would be necessary.

Such an array would double the number of baselines less than 300 meters. This would not only double the speed to reach a given surface brightness but also dramatically improve the *uv* coverage on such baselines. Combined with the total power system discussed above, it would make mosaicing practical with beams to 4-9 times larger in area than those of the current D array.

Table II. Possible Cassegrain Observing Bands for the Upgraded VLA

Band	Frequency Low (GHz)	Frequency High (GHz)	BW (GHz)	BW ratio	
L	1.20	1.75	0.55	1.40	keep
S	2.13	2.70	0.57	1.27	new
C	4.80	6.70	1.90	1.40	new
X	8.00	9.10	1.10	1.14	keep
Ku	12.00	18.00	6.00	1.50	new
K	18.00	26.50	8.50	1.47	new
Ka	26.50	40.00	13.50	1.51	new
Q	40.00	50.00	10.00	1.25	20 more

3. Very Long Baseline Array

Status

The VLBA will be operational in most major modes of observing at the end of 1994. All antennas were completed in 1993, and the correlator will be fully checked out in the first part of 1995. In the first quarter of 1995, the full complement of thin tapes will have been purchased and placed into use. Global VLBI Network sessions will continue and full-time VLBA observing will take place. In addition to the straightforward VLBI observations that are now possible, such as those of continuum and spectral line emission in both total intensity and polarization, some of the more advanced capabilities of the array, such as gated pulsar observations, will become fully available to the general astronomical community.

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 milliarcseconds 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.

The VLBA is outfitted for observations in nine frequency bands as shown in the Table III. All receivers are dual polarization. The receivers at 1.4 GHz and above contain cooled heterostructure field effect transistor (HFET) amplifiers from the NRAO Central Development Laboratory (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. There is a dichroic/ellipsoid system that allows simultaneous observations at 4 and 13 cm, primarily for geodesy and astrometry.

Table III. 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 VLBI 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 fringe mapping and utilization of the pulse calibration system. Documentation of the system is now the major goal. 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, 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 and have been tested. In late 1994, some of the core correlator code will be re-written with the goal of improving reliability to a level such that the correlated data can be expected to be correct with high probability. This level of reliability is needed to avoid slowing the throughput of the correlator by excessive scrutinizing of the output.

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 Array 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. During 1995, we expect to achieve full phase coherence by using a more complete and accurate geometric model based upon extensive geodetic and astrometric observations.

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 allow some performance at this frequency. Early measurements, with a substandard subreflector, gave an efficiency near 20 percent at 86 GHz, which is adequate. In 1994, the 43 GHz performance of the antennas was improved by a factor of two when a problem in the alignment of the subreflector was discovered and corrected. A remaining elevation-dependent astigmatism has yet to be fixed. We plan to install two 86 GHz receivers in the last quarter of 1994, 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 will take place in 1995. 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 requires substantial work in a number of areas, principally the correlator. In addition, the FX architecture allows frequency-dependent gating of the correlation for a pulsar. This requires software development in the correlator.

Scheduling and Observing

Astronomical observing on the VLBA will consist 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.

Three tape-recording formats have been in use for Global VLBI and VLBA observations: MkII, MkIII, and VLBA. The old MkII system will not be supported starting January 1995.

4. 12 Meter Telescope

The NRAO 12 Meter Telescope began as the 36 Foot Telescope, the telescope responsible for the birth of millimeter-wavelength molecular astronomy. Following a period of explosive growth in this new area of astronomical research, during which most of the dozens of molecular species known to exist in the interstellar medium were first detected at the 36 Foot, the telescope's reflecting surface and surface support structure were replaced and the 36 Foot was re-christened in 1984 as the 12 Meter. Subsequently, the scientific program has evolved from one dominated by observing programs in astrochemistry to one with a broader mix of studies of molecular clouds and galactic star formation, evolved stars, astrochemistry, and external galaxies. The 12 Meter is the only millimeter-wavelength telescope in the U.S. operated full-time as a national facility. More than 150 visitors make use of the telescope annually. It offers users flexibility and the opportunity to respond quickly to new scientific developments. Low-noise receiving systems at a wide range of frequencies, currently covering all atmospheric windows from 68 GHz to 300 GHz, are maintained. Operational reliability throughout is emphasized. Flexible spectral line and continuum backends allow the observer to match the instrument to the scientific goals. The development of multi-beam receivers and the new on-the-fly observing technique has inaugurated a new era of high-speed source mapping on angular scales complementary to those of the millimeter-wave interferometers. The new telescope control system offers great flexibility and provides a proven remote observing capability. It has also increased the efficiency and convenience of the 12 Meter Telescope; the experience gained will benefit future millimeter-array operation.

Present Instrumentation

Telescope

The basic specifications of the 12 Meter Telescope, its site, receivers, and spectrometers are:

Diameter: 12 meters

Astrodome with slit

Pointing accuracy: 5 arcseconds

Aperture efficiencies: 52% at 70 GHz
48% at 115 GHz
32% at 230 GHz
23% at 300 GHz

As many as four receivers are mounted simultaneously at offset Cassegrain foci on the telescope. Receiver selection is by means of a rotating central mirror and can be accomplished in minutes. The receivers are configured remotely from the control room with a computer-aided tuning system.

Receivers

The NRAO tradition of providing receivers equalling or bettering any others in the world is also true at millimeter wavelengths. A closed-cycle 4.2 K system capable of holding eight SIS receivers sharing the same dewar has been developed. A complete set of state-of-the-art, dual-channel superconducting-insulator-superconducting (SIS) receivers is operational over the entire range 68-300 GHz. The arrangement of several receivers sharing the same dewar is extremely effective in terms of cost, manpower, and in operational demands.

Table IV indicates the performance achieved by mid-1994.

Table IV. 12 Meter Receiver List

Frequency Range (GHz)	Mixer	SSB Receiver Temperature (K) Per Polarization Channel	Notes
68 - 116	SIS	60 - 90	
130 - 170	SIS	120	
200 - 260	SIS	200 - 400	1
260 - 300	SIS	400 - 500	
Eight-beam Receiver:			
220 - 250	8-SIS	200	2

Notes:

1. Receiver noise is around 200 K single sideband for most of the band, increasing somewhat at the high-frequency limit.
2. The 8-feed Schottky system has been upgraded to an SIS system. First testing on the telescope is expected in late 1994. Given noise performance is based on a prototype tunerless SIS mixer.

Note: All single-beam receivers have two orthogonal polarization channels. Receiver temperatures include all receiver optics.

Spectrometers

The following filter-bank spectrometers are maintained so that the astronomer will have access to the proper frequency resolution for a particular astronomical observation.

Table V. 12 Meter Filter Bank List

Resolution (kHz)	Number of Channels	Number of Filter Banks Per Channel
30	128	1
100	256	1
250	256	1
500	256	1
1000	256	2
2000	256	2

Note: All filter banks except the 30 kHz units can be divided into two 128-channel sections to accept two independent IF channels.

To enhance the telescope's spectroscopic capability and to accommodate the 8-beam receiver, a hybrid filter bank/autocorrelator is available. Its instrumental parameters are as follows:

- 8 independent, tunable IF sections;
- 1536 spectral channels (can be split into 8 sections);
- maximum total bandwidth options:
  - 1 x 2400 MHz
  - 2 x 1200 MHz
  - 4 x 600 MHz
  - 8 x 300 MHz
- frequency resolution (per channel): variable in steps of two continuously between 1.56 MHz and 24 kHz for each of two IF channels.

Note that the current instantaneous bandwidth is limited by the receiver IF bandwidth. The center frequency of the IF for some receivers is being changed from 1.5 GHz to ~3.5 GHz, to increase this instantaneous bandwidth beyond 1 GHz. This is particularly important for extragalactic observations of high redshift galaxies.

Future Instrumentation Plans

Most millimeter-wave spectroscopic studies of star formation, interstellar chemistry, galactic and extragalactic composition, etc., require observations of a number of molecules in a number of transitions, occurring at many different frequencies. These studies can be carried out most expeditiously, and most thoroughly, if high-sensitivity receivers are available for all the atmospheric windows and if a high-speed imaging capability is available at the most important wavelengths. Together, these requirements define the focus of the long-range plans for the 12 Meter.

All the developments described here are of immediate relevance to the 12 Meter Telescope, and most are equally relevant to the MMA.

One-Millimeter Imaging SIS System

Millimeter-wave telescopes inevitably have small beams, and hence, with the usual single-beam system, true imaging of large fields is particularly difficult and time-consuming. For large-scale imaging, the smaller diameter of the 12 Meter Telescope compared, e.g., with the IRAM 30-meter telescope in Spain, is no disadvantage. We plan to provide a powerful imaging system at our optimum wavelength of 1.3 mm.

To this end, the 8-feed Schottky mixer system was made available during the 1989-1990 season. The system was a great success, in spite of compromises in the implementation. (The hybrid spectrometer was not yet operating with the full versatility of its original design, and the telescope control system at that time severely restricted the convenience and efficiency of the system.) The 12 Meter Telescope now operates under a completely new control system using modern hardware, and we will finish the planned implementation of the hybrid spectrometer by the end of 1994.

The eight-feed Schottky system has been upgraded to use SIS mixers, thereby giving state-of-the-art sensitivity in all feeds. This upgraded system should become available to observers late in 1994. An extension to a 32-feed SIS system is planned at a later date. The key to this development is the backend electronics. We are cooperating with the Green Bank Telescope correlator group, and intend to use the same printed circuit cards and chips as are being developed for that project, for the multi-feed digital auto-correlator spectrometer for the 12 Meter Telescope. Of course, a 32-feed system puts severe demands on the computer hardware and software. The telescope real-time control system has been completely replaced with a modern design which offers great flexibility for future developments. Already, remote observing, controlling the 12 Meter telescope over a wide-area network has been demonstrated, and is expected to become a more common mode of operation in the next few years. Recently we have concentrated on improving the observing efficiency of the telescope and on developing and implementing new observing techniques. The data acquisition rate will have increased by between 1 and 2 orders of magnitude. The postprocessing environment is becoming a network of modern workstations. We have begun to build this network with existing funds, but a great deal of new computer hardware and software development will be required in the next three to four years.

Future Single-Beam Systems

Experimental HFET amplifiers have been tested in the CDL which may be capable of performance competitive with SIS devices at 3 mm. As soon as feasible, we intend to construct a specialized continuum receiver using HFET devices, for the 3 mm band. This receiver will have an instantaneous bandwidth of up to 20 GHz, and will give a continuum sensitivity far higher than any existing coherent receiver or bolometer. Again, this experience will be invaluable later for the MMA, and may simplify the implementation of array receivers at 3 mm and longer wavelengths.

Antenna Improvements

With the improved surface accuracy, operation of the 12 Meter Telescope at the highest frequencies (~300 GHz) is becoming more productive. This puts a more critical demand on the pointing characteristics of the telescope. In order to improve the pointing, we have implemented several upgrades in the past year. We are also installing an improved real-time monitoring system for movements of the prime focus, utilizing a laser and x-y translation detector. We have reevaluated feedleg insulation and are installing blowers to circulate air through the interior of the feed legs. We expect to implement additional instrumentation (inclinometers, strain gauges, temperature sensors), replace the feed legs with a carbon-fiber design giving less temperature dependence and less aperture blockage, and install a sun screen to reduce thermal distortions of the telescope during daytime operation. We now routinely use an auxiliary optical pointing system to determine the telescope pointing model and to diagnose pointing anomalies. We intend to explore a higher level of automation, with the possibility of offset guiding on optical stars to give accurate tracking of weak sources.

Polarimeter

We have constructed a polarimeter for the 12 Meter Telescope, which will be used to study linearly and circularly polarized emission in both the broad-band continuum and the spectral-line mode. This device became available in mid-1994. The design uses an adjustable grid and plane reflector combination, is quite compact, and will become a prototype design able to give similar capability to the MMA. A future project is to construct a version for a wavelength of 1 mm.

Telescope Control, Data Acquisition, and Data Analysis Improvements

New enhancements continue to be incorporated into the telescope control system. The analog servo system that positions the telescope will be upgraded to a fully digital system. This should reduce the settling time required after telescope movement and could result in a 10 percent or more improvement in the duty cycle of most observing modes (note that 10 percent improvement in observing efficiency is equivalent to approximately 30 days of observing time in a typical season at the 12 Meter). The user interface has been enhanced to allow the observer more direct control over the telescope. The new on-the-fly observing mode will now become a routine mode for continuum observing, as well as for spectral-line observing, in 1994. When using this technique, the observer will make several rapid passes over the field of interest, and average the results to improve signal-to-noise. The observing efficiency will be much improved, because most of the dead time required to move the telescope beam from one discrete point on the sky to the next will be avoided. Several rapid maps should produce superior results to one slow one, because drifts in the receiver and atmospheric absorption will be minimized. Such observing techniques as this will require more advanced data-handling facilities than presently available. We plan a concerted effort at advancing imaging software during 1994-95.

Longer Term Future Plans

In addition to continued improvements in the 12 Meter, the Tucson staff will play a growing role in the development of the Millimeter Array. As the MMA project develops, there will be the necessity for real hardware design, prototyping, and testing, including multi-band, millimeter, and submillimeter-wave receivers, digital spectrometers, and continuum backends. Software evaluation in astronomical observations such as described above is another important area where the prototyping done at the 12 Meter will further the development of the MMA. Many of the projects already underway in support of the 12

Meter Telescope will become prototypes for, or otherwise contribute to the eventual MMA project. The Tucson staff are already actively participating in site testing for the MMA, with the construction of a portable centimeter wavelength interferometer to be used to study atmospheric phase instabilities at potential MMA sites. An innovative slant-axis antenna design for the MMA is being explored, and shows great promise for a robust, high precision antenna. It is anticipated that Tucson participation in MMA development and support activities will continue to increase in the coming years.

5. 140 Foot Telescope

In 1995 there will be several major changes to the instrumentation of the 140 Foot Telescope, most of them driven by use of the instrument as a test-bed for GBT hardware and software. The mechanical components of the telescope are being kept in good repair, and long-term maintenance procedures are being performed. While it is anticipated that the 140 Foot Telescope will be removed from service as a visitor facility when the GBT comes into operation in 1996, it is being maintained so as to operate reliably up until that time. In the past year a number of major hydraulic systems were overhauled, and the cables that brace the feed support legs were replaced.

Telescope users in 1995 will benefit from items destined for the GBT that will be brought into operation first on the 140 Foot. The Cassegrain receivers that have been built for the GBT will be installed on the 140 Foot to provide extra bandwidth and stability, and a sensitivity comparable to or better than the existing 140 Foot receivers. The upgrade to the memory of the spectral processor is now complete, and control has been switched from the Masscomp computer to a new Sun workstation. In 1995 the spectral processor will be completely switched over to GBT software and a new powerful computer to control it will be installed. This will allow pulsar searches to proceed at a much higher data rate than possible with our current computer, and will give users a chance to experience the look and feel of the GBT software. The GBT telescope control software will also be installed on the 140 Foot and it will used for certain types of observation. The users will thus have the benefit of the modern software and hardware, and the GBT staff will be able to test and refine their instruments under real observing conditions. By the end of 1995 all 140 Foot receivers above 8 GHz will be replaced by the new ones built for the GBT and only the

Model IV autocorrelator will depend on the Modcomp computer. This should provide us with a significant maintenance savings over the current system.

In early 1995 a VLBA back-end will be installed at the telescope, making it entirely compatible with the VLBA for interferometric observations. The telescope will be connected to the site-wide fiber optics network which will distribute high-quality time and frequency signals over the site from a single timing center. It will also allow control and IF signals to be sent around the site to locations where equipment might be shared among experiments.

A project is underway to develop a timing center and timing signal distribution system for the Green Bank site. The signals will be distributed on optical fiber cables installed in conduit buried three feet below ground to reduce diurnal temperature fluctuations. The conduit is already on site and is now being installed. It will proceed up the Interferometer baseline to the GBT site and then to the 85-1 control building. From there conduits will branch to the 140 Foot Telescope, to the new U.S. Naval Observatory (USNO) 20 meter, and to the Orbiting VLBI (OVLBI) earth station antenna, and the Jansky Lab.

The primary frequency standard will be the USNO Sigma-Tau hydrogen maser located in a clock room in the Interferometer control building. The clock room will accommodate up to two masers and a rack of clock equipment. Temperature variations within the room are controlled using an inexpensive thermal mass.

Time is kept by a commercial digital clock which runs on a 5 MHz signal from the maser. The clock produces a 1PPS output which is distributed over the site, primarily for use in back-end hardware to synchronize clocking of data. The digital clock contains an IRIG-B time code signal generator, and this output is also distributed as required by the GBT monitor and control design. The digital clock output can be synchronized to an input pulse which will come from a Globel Positioning Satellite receiver.

A LO reference distribution system takes sine-wave signals generated in the maser and distributes them to phase-lock local oscillators at the telescopes. Some type of round-trip measurement system with picosecond resolution will be installed to compensate for varying propagation delays caused by residual temperature fluctuations in the conduit and any open-air fiber runs at the telescopes.

IV. TECHNOLOGY DEVELOPMENT

Development of new instruments and software for the NRAO telescopes is an ongoing effort that involves intellectual resources at all the sites. Because there are many problems common to all the NRAO facilities, we attempt to share solutions developed for one set of problems with all the other sites. One efficient way of doing this is to maintain, insofar as it is possible to do so, similar devices and software at all the sites. Another approach is to separate development work from telescope maintenance activities and to consolidate both enterprises as much as is possible. Both these approaches are integral to the operation of the NRAO. The Research Equipment plan includes both electronics and computing equipment. The Research Equipment Plan for 1995 is outlined below separately for electronics and computing and is summarized in Tables IV and V. Also included in this section is a description of equipment needed for day-to-day operation of the Observatory, so-called Operating Equipment.

1. Common Electronics Development

The Research Equipment Plan utilizes electronics and software developed in Charlottesville for common use at all NRAO sites.

Cooled HFET Amplifier Development

Centimeter-wave radio astronomy receivers (< 50 GHz) now almost universally use cooled HFET amplifiers as the low-noise input amplifier. The NRAO Central Development Laboratory has worked on the development of these amplifiers for many years and is largely responsible for their wide acceptance by the radio astronomy community. HFET amplifiers are reliable, stable, and can be made up to an octave in bandwidth without significant penalty in noise.

A recent program has been started to develop HFET amplifiers in the 60-115 GHz frequency range. We have demonstrated them to be able to approach performance comparable with the noise performance of SIS mixers. Their comparatively low cost, high reliability, and ability to operate at a temperature of 15 K instead of the necessary 4 K for SIS mixers make them the preferred receiver for arrays up to 115 GHz (VLBA and MMA).

Since HFET's suitable for amplifiers above 40 GHz are not commercially available at the moment, we will continue our cooperation with several industrial laboratories involved in HFET development. NRAO has contracted with Hughes Research Laboratory to manufacture several wafers of indium phosphide (InP) HFET's which are expected to be similar in performance to devices that have been evaluated by NRAO during 1993-1994. These devices will enable NRAO to develop and fabricate sufficient amplifiers in the frequency range 60-100 GHz to meet VLBA and Tucson requirements. These devices will also improve the performance of lower frequency amplifiers in the frequency range 5-50 GHz and, consequently, will be used to upgrade VLA, VLBA, and GBT receiver performance.

SIS Mixer Development

The design and fabrication of Supercomputer-Insulator-Supercvonductor (SIS) mixer receivers is work done at the CDL in collaboration with the Semiconductor Device Laboratory at the University of Virginia. The receivers which are the product of this collaboration operate at 65-300 GHz on the 12 Meter Telescope and, additionally, SIS devices have been supplied to several other observatories. In 1994 a mixer specifically designed for 68-90 GHz (the present receivers use modified 90-115 GHz mixers) is now being fabricated. It is expected to have comparable performance to our 90-115 GHz mixers.

We shall continue work on two new designs for higher frequencies: (i) a fixed-tuned mixer of a completely new design, initially for 200-300 GHz, and (ii) a fixed-tuned mixer for 260-360 GHz based on the successful tunable NRAO 2 mm mixer. In addition to its immediate applications on the 12 Meter Telescope, this work is important for the MMA.

Table VI. Electronics Equipment Plan

	1994 (est)	1995
Laboratory Test Equipment	0	100
Miscellaneous Projects	72	100
Very Large Array		
1.3-1.7 GHz Improvement	70	
RFI Shields	40	
4.8-6.7 GHz Receiver	10	
12.0-15.4 GHz Receiver	10	
18-26.5 GHz Receiver	10	
Array Computing	63	
Very Long Baseline Array		
80-92 GHz Receiver	10	

	1994 (est)	1995
12 Meter Telescope	30	
SIS Receivers	26	
Spectrometer	5	
VLBA Maser Link	34	
Control/Analysis Computing		
GBT Telescope		
Prime Focus Receiver (supplemental)	0	50
Gregorian Receiver (supplemental)	0	100
Spectrometer	0	
Time/Freq. Distribution	44	
Analysis Computing	35	
Common Development		
Millimeter SIS Mixer Development	30	
HFET Amplifier Development	30	
TOTAL	519	350

2. Computing

Common Software Development

Computing systems at the NRAO are indispensable for NRAO operations and support of NRAO users and visitors. Besides the obvious necessity for computer control of the systems which 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. Radio astronomy is unlike many other scientific disciplines, in that computer analysis is fundamental to the process, rather than merely a useful adjunct to scientific analysis.

Maintaining observational and scientific capability is the fundamental goal of computing at NRAO. Implicit in this goal is the necessity of constant striving to keep ahead of computing demands at the NRAO. Computing systems and software should not be the limiting factor in the science which users are able to accomplish with NRAO facilities. This means that as observational requirements on computing increase (driven by improved observational methods, new technological capabilities, and deepening scientific understanding and knowledge), the Observatory must respond.

For 1995, the following areas are priorities for computing equipment and support; at the request level of funding, the planned budget for these activities, shown in Table VII, is inadequate.

Table VII. Computing Equipment Plan

	Project Cost (k$)	1995 (k$)
System Upgrades	480	25
Networking	450	
High-End Computing	270	
Engineering Computing	160	
VLA On-Line Upgrade	150	75
Mass Data Storage	240	
Total	1,750	100

System Upgrades

During 1995, approximately one-third of the workstations at the NRAO should be upgraded to more capable systems. These machines were purchased in 1991 and earlier, and are showing their limitations. Their upgrading or replacement is necessitated by the increasing demands on computational capability at the NRAO from both increased demands from NRAO users and increased observational capabilities brought about by technological advances and improved observational techniques. This level of replacement will allow most workstations at the NRAO to be replaced or upgraded by the end of their useful lives (typically 3-4 years for scientific workstations). If this level of replacement and upgrading is not maintained, NRAO risks returning to the situation of a few years ago, where use of observational facilities was restricted solely to prevent overloading of data-reduction capabilities. These upgrades are especially urgent in view of the VLBA becoming fully operational in 1995, and as a result of the newly developed mapping capabilities at the 12 Meter Telescope. The cost of this effort will be $480,000 for hardware acquisition during 1995.

Networking Upgrades

At each of its major sites, NRAO operates a complex networked computing environment. This offers numerous advantages for efficiency and flexibility in meeting the needs of computer users at NRAO. The installed networks are beginning to show their limitations, particularly in the area of data bandwidth between machines on the networks. One of the salient features of radio astronomy is the large sizes of typical data sets. Medium bandwidth links between machines on the Local Area Networks result in a bottleneck and reduce the effectiveness of sharing computing resources at a site. Resolving this situation will allow increased efficiency in the use of computers at the NRAO and allow more flexibility in meeting future computing demands.

The specific goal is to begin the process of upgrading the networks at the sites to provide T1 capability to most of the workstations at each of the sites. This process should be accomplished in time for major new observational capabilities and opportunities at NRAO associated with the GBT and OVLBI, as well as the VLBA and the 12 Meter. A related goal is providing high-speed links between NRAO sites and between NRAO and external institutions. Current network connections only allow limited access for remote observers; the pioneering efforts at the 12 Meter to provide support for remote observers should be enhanced and expanded to provide such capabilities for remote observer access for NRAO's other instruments.

Improved networking would yield dramatic improvements in the ability of NRAO users to share data between the sites, and would also allow the current software distribution methods between the sites to be improved. Presently, major packages are upgraded via distribution of software in a batch mode. Wide bandwidth links would allow more centralized software distribution, and would result in improved user support.

The estimated cost for improving the performance of the computer networks at NRAO will be $450,000.

High-End Computing

Recent budgets have forced NRAO to neglect areas related to solving the high-end computing problems faced by NRAO. As a consequence, several research areas are beginning to feel the pinch. During 1995, two efforts can alleviate this situation. First, acquisition of three high-end workstations for addressing large problems should proceed. These machines would provide facilities to address computing problems which currently take several months on NRAO's existing workstations are therefore impractical for most observers and NRAO visitors. Estimated cost for this initiative during 1995 will be $270,000. This will have the greatest impact on VLBA science and VLA science during 1995.

Second, a detailed review of the even larger scientific problems will proceed during 1995 to identify problems which require computer resources beyond those either currently or likely to be available within the NRAO. The results from this study will guide gaining access to or the acquisition of computing systems capable of addressing the computational problems that the current mix of workstations at NRAO cannot address during 1995 and beyond. The bottom line is that a number of important scientific problems are being neglected because of the lack of large scale computing at NRAO. Final costs of this initiative are presently undetermined; during 1994 approximately $50,000 will be needed to explore the capabilities of existing large computer facilities and identify the most cost effective solutions for NRAO to pursue. This effort will be complementary to the upgrade effort described above.

Engineering Computing

NRAO is pursuing several initiatives leading to development of major new observational instruments or to greatly enhanced capabilities for existing instruments. Chief among these efforts are the Green Bank Telescope, the Millimeter Array, and the VLA upgrade. These projects are heavily dependent on the use of advanced engineering workstations to carry out various aspects of the design and fabrication for these instruments, even at a very early stage. Presently, many engineers at NRAO are faced with carrying out design efforts using obsolete or inadequate workstations and PC's. Rectifying this situation will increase the productivity of NRAO's engineers and the effectiveness of NRAO's operations over the long term. Although efforts in this area were planned for 1994, the budget situation forced these plans to be deferred. Estimated cost of this effort during 1995 will be approximately $160,000. This will allow both the acquisition of appropriate workstations and the required commercial software.

VLA On-line System Upgrade

The current VLA on-line control system is nearing the end of its useful lifetime. The computers and disks used in the system are nearly ten years old, and are a growing maintenance problem. Some of the disk systems, for example, are completely obsolete and must be maintained by keeping a large number of such ancient disks as spares, since support and repair from the manufacturer is no longer available. This situation must be rectified before any disastrous failures occur by beginning the effort in 1995 to upgrade and replace the aging systems with modern systems. The effort will yield several benefits, including a modest reduction in downtime for the VLA, a large reduction in risk of major system failures, and lay the preliminary ground work for any upgrades to the VLA which may occur later in the 1990's. The effort will cost approximately $150,000 during 1995.

Mass Data Storage

One of the hallmarks of radio astronomy is the large volume of data which must be managed, stored, and reduced. Three systems are going to stretch the capabilities of NRAO's computer facilities to deal properly with the expected data volume. First, results are beginning to be available from two large-scale surveys being conducted using the VLA. In order to provide broad access to these results by the astronomy community, NRAO will be making them available on-line, via the Internet. Although NRAO will not be the only such source for these data, NRAO is certainly the only institution with a long-term interest in maintaining access to these surveys. Depending on how rapidly results from the surveys become available, several score gigabytes will be needed during 1995. Ultimately, as these surveys are completed, versions will be made available through other distribution media (such as CD-ROM).

Second, new techniques and capabilities at existing NRAO instruments (such as On-the-Fly imaging at the 12 Meter or the new Green Bank spectral processor) are increasing the amount of data which must be handled by off- line data reduction systems, and the amount of data which must be available on-line at a given time is increasing. Current facilities at sites for managing voluminous data sets are inadequate, with particularly lengthy delays caused by lack of data storage space and limited tape drives.

Finally, and most importantly, the VLBA will become fully operational during 1995. Previous estimates were that the VLBA would place approximately the same load on data reduction facilities at NRAO as the VLA; experience so far suggests that this may be an underestimate in the data-handling arena. An 8-hour, VLBA-only, observation of a single source in continuum mode isgreater than one gigabyte in size, for example. Substantial improvements in data storage and tape facilities at the AOC will be needed during 1995 to meet the expected demand.

Total costs for data storage and handling facilities at NRAO during 1995 will be $240,000.

Computing Support

Development of new instruments at NRAO (e.g., the VLBA and soon the GBT) and enhanced capabilities of existing instruments (e.g., new techniques at the 12 Meter and the 140 Foot) have increased the need at the Observatory for computing support personnel. Unfortunately, during the past few years lean budgets at NRAO have led to reduced personnel in computing support and software development. As a result, the support provided to computer users is becoming increasingly inadequate. Support personnel in computing are often forced to work in crisis mode and must neglect long-term planning for enhancing computing support.

During 1995 NRAO should move to address critical shortages in certain areas of computing support. Particular needs for support personnel exist at all four of NRAO's computing sites: To solve problems common to all the observing sites, there is a need for a general programmer to address scientific visualization and algorithm development. In Green Bank, computing hardware and software support is done in an *ad hoc* way in certain areas, reducing the effectiveness of the scientific and engineering staff in Green Bank. An additional support position would allow the site wide coordination of computing support. In Socorro, at least two new positions are needed to alleviate problems in software support, especially for PC's, and programming support, particularly in the area of database support for the maintenance database system. Finally, in Tucson there is a desperate need for additional programming support to take advantage of the great scientific opportunities opened up by the development of advanced "On the Fly" observing techniques.

The total number of new positions in computing at NRAO which should be created in 1995 is five. These positions would have an impact of about $150,000 on the 1995 budget and about $250,000 in per year in subsequent years. The positions are incremental to the financial and personnel tables given in Section IX.

AIPS++

The AIPS++ project is an attempt to create the next generation data reduction and analysis package for radio astronomy. Its origins can be traced to concerns within NRAO and other institutions that current data reduction packages do not provide the flexibility and future potential desired, despite the present success of these packages. AIPS++ should be a considerable improvement in terms of programmability (at various levels), maintainability, portability (including distributed processing), and exportability. Because such an undertaking has such broad utility, seven radio institutes: the Australia National Telescope Facility, the Berkeley-Illinois-Maryland Array consortium, the Canadian Herzberg Institute (operating the James Clerk Millimeter Telescope and Dominion Radio Astrophysical Observatory), the Netherlands Foundation for Radio Astronomy, the Nuffield Radio Astronomy Laboratories at Jodrell Bank in the United Kingdom, the Tata Institute for Fundamental Research in India, and the NRAO, which among them represent the majority of large radio synthesis telescopes worldwide, have joined forces in the AIPS++ Consortium. The project started in earnest in

January 1992. Since then, the infrastructure has made considerable progress, and initial applications are under development.

Release Plans

The first public releases for AIPS++ are expected during 1995. The first release is scheduled during the first quarter of 1995. This release will be an "alpha" release, meaning that while the package will have useful functionality, certain features will be unavailable, and unexpected bugs are possible. It will be released to selected users who will be asked to carefully evaluate what the package does, what works, where problems lie, and suggest improvements. The alpha will be followed by a beta release, presently planned for the third quarter of 1995. Beta-level software provides a reasonable feature set for testing and evaluation by selected users and volunteers; bugs and problems are still expected, but the features of the software are hoped to be relatively stable. The beta version of AIPS++ will contain much that is new, as well as providing a useful core functionality. The exact dates for the beta release depends on the success of the alpha version and resolution of any problems discovered. Finally, current plans call for the release of the first official version of AIPS++ during the first quarter of 1996. This will be the first broadly distributed version of AIPS++.

3. Operating Equipment

Funding for Operating Equipment provides for the replacement, upgrading, and acquisition of equipment, including maintenance and shop equipment, office and library equipment, vehicles, living quarters furnishings, and building equipment. As in previous years, funding for personal computers and items of other major office equipment has been substantially reduced.

The NRAO has supplemented its funds for Operating Equipment by acquiring property under the Government surplus program. During 1994, we obtained approximately $630k in surplus equipment, including diesel generators, 4x4 truck, dump truck, and fork lift. Although this program has been a tremendous benefit to NRAO, we cannot depend on this source for equipment when planning future needs. The equipment is only available on a first-come, first-serve basis.

The 1995 funding requirements are estimated at $400k, but the expenditure planned at the request level budget is no more than $50k.

V. MAJOR CONSTRUCTION: THE GREEN BANK TELESCOPE

Antenna

Due to its shear size, the most visible progress on the Green Bank Telescope project during the last year has been on the structure itself. The alidade is now virtually complete up to the elevation bearing level. The electrical power system, which includes installation of the antenna cable wrap, power lines, and transformers on the antenna alidade, was successfully completed and the switch-over to permanent power was made in late 1993. The structure has been rotated 180 degrees in azimuth using one of the four actual servo cabinets and two 30 horsepower motors along with their gearboxes, brakes, and tachometers. The ability to rotate the alidade represents a significant milestone since it allowed an early checkout of the operational capability of the servo system and drive train while providing the contractor with the ability to reach any part of the structure with the derrick tower crane. The elevation bearing support weldments, at approximately 80 tons each, have been installed at the top level of the alidade towers, about 165 feet above the ground. The alidade manlift has been finished and now extends to this level as well. The elevation bearing platforms also have been installed.

Once all field welding is complete, the structure will be ready for the installation of the elevation shaft, wheel, and box structure which will occupy the remainder of 1994 and the first half of 1995. As shown in the photograph, the temporary scaffolding tower which will support the elevation shaft and wheel during the erection process is already in place. Sections of the wheel support members have been arriving from the steel fabricator and are currently being welded on the ground into 36-inch square, 105-foot long spokes which attach the elevation wheel to the elevation shaft.

Concurrent with the installation of the elevation wheel and box, the entire reflector backup structure will be constructed on the large concrete pad provided for this purpose. Concrete piers have been incorporated in the pad to exactly duplicate the sixteen hard points on the box girder which support the entire reflector backup structure. The backup structure will be built to consist of 22 modules. These modules, after construction on the ground, will then be lifted into place with the derrick crane. A 60-foot tall tower topped with a survey/measurement house has been erected at the vertex of the reflector to allow the precise measurement and alignment required during the construction of the back-up structure. This activity will begin in late 1994 and installation will extend through early 1996.

CONSTRUCTION PROGRESS OF THE GREEN BANK TELESCOPE (GBT) AUGUST 1994

NATIONAL RADIO ASTRONOMY OBSERVATORY - Operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

Feed arm erection will begin in mid-1995 and continue until late in the year. The subreflector will be added to the structure in late 1995.

Panel fabrication has begun at the contractor's facility. Testing has been done to determine the desired combination of rivets and adhesive to attach the surface skins to the Z-stiffeners. The quality and strength of the adhesive has proven to be so effective that it is now considered a structural connection rather than a flexible shim. This allows a larger spacing between rivets which can lead to better manufacturing accuracy. Panel fabrication will continue through the first three quarter of 1995. The surface panels will be installed during the spring and summer of 1996, in anticipation of project completion in late 1996.

With respect to the design, advanced analysis of the GBT pointing performance has provided simulation results so far which indicated very small structural excitation due to azimuth and elevation axes motion. The simulation result is based on the GBT structure finite element model and drive and control system with multiple degrees of freedom, as compared to the single axis lumped mass model with a single degree of freedom used by the servo contractor. The residual RF pointing error due to structural excitation is shown to be better than 0.0002 degree (0."72) during tracking. This indicates that during periods of no wind the limiting operating frequency of the GBT due to drive-induced pointing errors is 50 GHz.

Project Phases

The construction project completion and operation of the GBT 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.

During Phase I, the antenna will be transformed into a functioning radio telescope, complete with 2,200 active surface actuators (already installed by the contractor during Phase 0 in a zero position), 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 Phase I telescope will be capable of 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. Phase II will allow operation up 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 high frequency operation.

Make Come True Program

To insure that the final design of the GBT is translated into an exemplary structure, NRAO has instituted a Make Come True Program. The program consists of four basic facets.

The first facet, which has been completed, was a rigorous verification of the contractor's final design. Following the design verification, NRAO worked in conjunction with JPL to conduct an optimization of the structural members. The final analysis provided further evidence that an optimized design has been achieved for the selected GBT configuration.

In the second facet NRAO has implemented a special program to monitor the manufacture of all parts in compliance with the design. In addition, the software provides for the smooth flow of shipments of over 11,000 structural members to the site, guides on-site storage, and helps insure that the members are oriented and installed correctly.

The third facet is a weight control program. The optimization program has identified a few sensitive members where a small weight change will have an amplified negative affect on surface accuracy. These members, as well as the overall tipping structure, will be carefully monitored for weight, starting with the design drawing and following through to the final installation to insure the antenna weight is controlled.

Finally, the quality assurance (QA) program, instituted early in the project will be carried through to completion. Since the entire structure is welded, a particularly important aspect of the QA program is the control of both shop and field welding, with a particular emphasis on the difficult field welds. The certification of welders, qualification of weld equipment, specific attention to welding procedures, and ultrasonic testing of shop welds and critical field welds are all working in conjunction to produce a sound structure.

Schedule

The 1994 Program Plan reported that the GBT scheduled completion date would be extended. This extension has been indicated for some time and has been reported in various previous documents. Much progress has been made on the GBT in all areas during the past year and 1995 will be a busy and productive year for the project, as reported below. However, as progress has been made, particularly in the areas of structural design, fabrication, and erection, a fuller understanding of the complexities and magnitude of the structure, and the time required to achieve completion of a structure of the size and nature of the GBT, has been gained. Recent reviews of the status of the structure and re-evaluation of the remaining work have led the contractor to submit a schedule revision request for NRAO review which indicates the antenna will be delivered in late 1996. NRAO is currently reviewing the submittal.

While such a delay is undesirable, it could benefit the project at the NRAO in some ways, including adding time for the GBT team to study all elements and subsystems of the telescope design, resulting in many refinements. It would also provide the opportunity for further development of in-house systems (electronics, active surface, monitor and control, and data analysis) and additional optimization and debugging of subsystems prior to their installation on the telescope. All of this in principle will allow for a quicker conversion from the construction project to a fully operational radio telescope.

The proposed schedule delay does not come without a cost. NRAO is reviewing the project budget with an eye towards a final construction project close-out in late 1996. The continuation of the program to that point requires a combination of two things: an orderly reduction in project staff and reduction in certain technical aspects of the project. Beginning in 1995, personnel previously included in the construction budget will start to return to NRAO operations payrolls. Over the next two years a planned transition of construction employees to operations will occur. The implementation of this plan is essential to the effective operation of the completed GBT. It is assumed in the project budget. A rigorous review of the in-house technical programs is underway and may lead if necessary to a rescheduling, reduction in specifications or elimination of certain projects such as the local control building, the 40-52 GHz receiver, the autocollimator and floodlight systems, and the spectrometer.

Electronics

Through mid-1994, most of the GBT electronics systems have been designed and first devices constructed and tested. The 18-26.5 GHz, 12-15.4 GHz, and 8-10 GHz receiver front-ends are completed and tested. The prime focus front-end box and the 3.95-5.85 GHz front-end are nearing completion. Fabrication of the 1.15-1.73 GHz front-end is underway. A Gregorian feed rotator mechanism and the turret cable wrap assembly have been fabricated and tested successfully. The receiver room local oscillator and IF racks are assembled and tested. First modules for the IF optical links connecting the receiver room to the equipment room have been constructed and tested, and replication of these modules is underway. Construction of the first frequency converter module which is required to support existing and planned back-ends has started. A correlator for holographic surface measurements has been completed and tested in measurements on the OVLBI antenna in Green Bank. The spectral processor, which was originally designed for use on the 140 Foot, has been upgraded, providing both additional memory and compatibility with the GBT monitor/control technology. By the end of 1994, the 3.95-5.85 GHz and 1.15-1.73 GHz front-ends and sufficient electronics for four IF channels to support existing back-ends should be completed. The new 16-channel continuum back-end hardware should be completed, and detailed design for the new 256 K channel spectrometer will be well underway. Design for the final two Gregorian front-ends (1.73-2.60 GHz and 40-52 GHz) will be started. Completion is scheduled prior to initial operation of the GBT.

During 1995, the electronics group will continue the hardware design and construction tasks currently underway, and will complete construction of the set of electronics planned to be ready at initial outfitting of the telescope. The initial set of feeds and receivers will be completed. Efforts will be concentrated on a tertiary reflector system design, expected to be used for beam switching and fast pointing corrections. The racks to be installed in the receiver room and control building will be assembled and tested and made ready for installation. Cabling plans and other preparations for outfitting the antenna will be completed, and materials required will be purchased.

The extended antenna structure construction schedule makes it feasible to utilize the 140 Foot Telescope as a real-world test bed for many systems. A program has already started to install GBT front-ends on the 140 Foot. The 18-26.5 GHz and 8-10 GHz front-ends have been mounted in the 140 Foot Telescope Cassegrain cabin and the 140 Foot Telescope feed horns were adapted for use with them. The 12-15.4 GHz front-end will be mounted soon. This test bed program gets significant portions of the GBT hardware in the hands of users in time to catch design problems and provide feedback on the monitor/control implementations, and could significantly shorten the period required to bring the GBT on-line. We will continue, and perhaps extend, this program to include portions of the GBT IF and LO hardware.

Open Loop Active Surface

Much progress has been made in the open loop active surface area during the last year. Deliveries of the 2,400 actuator assemblies continue. Testing of final version actuators has continued on the 85-1 Telescope test stand and the operational goal of 2,000 hours has now been exceeded by over 3,000 hours. The burn-in of power supplies for the motors and control modules has continued, and all units have performed satisfactorily both electrically and thermally. Control system panel construction has continued. Also, integration of the monitor and control system software with the actuator control system software has begun. This effort will lead to the ability to control and monitor the actuators through a control panel on a network workstation.

The open-loop active surface project will undertake several new tasks during 1995. They include installation of the active surface control room wiring and hardware which is to be performed while the actuator control room is still on the ground. NRAO plans to assist the contractor in examining the actuators and testing the associated cables after installation to assure that they have not been damaged during erection of the structure and installation of components. Additional cabling and hardware installation which must be done on the structure will begin. The initial control software will be completed in 1995, and integration and system check-out will begin.

Closed Loop Active Surface and Precision Pointing

In 1995, the completion of all the hardware and software necessary to implement the proposed precision pointing and closed loop active surface systems on the GBT will be accomplished. Progress during 1994 has been most encouraging. The electronics for twenty range finders is nearing completion, and the mirror assembly, the major component in the optical head of the range finders, is in production in the Green Bank shop.

The major task during 1995 will be a demonstration of a limited version of the proposed pointing system on the 140 Foot Telescope. Four laser range finders, in the configuration to be used on the GBT, will track various targets on both the stationary and moving parts of the 140 Foot structure. Test range measurements (with many redundant measurements) will hopefully confirm the assumptions regarding the behavior of the atmosphere. The range finders will be controlled over ethernet from a location over a mile away, thereby creating an environment very similar to the installation on the GBT.

During 1994, the original three range finders have continued to operate in an outdoor environment. These range finders have provided a continuing experimental platform for testing software and supporting experiments regarding the behavior of the atmosphere. We anticipate that these range finders will remain in operation until the GBT is operational.

Work on the panel setting tool also will continue during 1995. The prototype tool, along with the associated hand-held computer, has been refined during 1994. The addition of a bar code reader to the tool will result in a fast, convenient means of reading panel information into the computer, thus facilitating the initial panel setting. Several of these tools will be fabricated during 1995.

Work on the autocollimator and quadrant detector systems for pointing the GBT will continue during 1995, although our emphasis will be on the laser pointing system, with the other two systems serving as auxiliary devices.

Servo

Although the GBT servo system is being developed by the antenna contractor, NRAO maintains a high level of involvement due to the critical importance of a successful servo system to the telescope's operation. The servo system includes azimuth, elevation, feed arm, and subreflector servos. During 1995, acceptance testing of the feed arm servo system will be performed at the contractor's facility. Also, the subreflector positioning mechanism will be calibrated following its delivery to the construction site in Green Bank. The permanent azimuth and temporary elevation system will be installed on the telescope in early 1995. In addition, the system documentation package will be delivered. The permanent elevation system will be installed during the first quarter 1996, and final acceptance of the servo system will come at the conclusion of field tests.

Monitor and Control

The remainder of 1994 will see the completion of a "mini-GBT monitor and control" system at the 140 Foot Telescope. This includes the monitoring and controlling of: the main reflector with a traditional pointing model and the production of data associated parameters; the spectral processor; the Cassegrain receivers; the timing center; and, the weather station. The system also includes the introduction of Glish for data transfers and command-line configuration. Also, the message system will be complete. Data will be written in FITS providing access by PV-WAVE and other FITS compatible programs. A graphical user interface (GUI) provides user access through virtual control panels to all of the above-mentioned equipment. This functionality represents the completion of our core software that performs the lion's share of the coding needed for integrating any system into the telescope. The next year will mostly consist of adding subsystems and the code specific for them to the telescope, improving robustness, and providing a modern observer interface. The universal local oscillator software will be finished and operational. The work started in electronics on the continuum receiver will be completed and the software for the new spectrometer will be begun in 1995.

Serious development on the observer's interface will be in progress during 1995, including integrating with the analysis system, sequencing scans, handling calibrators, accepting all coordinate reference systems, VLBI observations, and remote observing. Heavy use of the simulator is planned in order to improve the user-interface both by getting feedback from astronomers and by making the system more familiar to potential observers before the GBT comes on line.

Hardware and documentation will be developed for various monitor and control subsystems, including Irig Timing Distribution, MCB, Position Computer Chassis, Servo Monitor Chassis, Telescope MCB & IEEE-488 Chassis, Control Room MCB & IEEE-488 Chassis, IEEE-488 distribution, and telescope Local Area Network. The various racks and chassis required for monitor and control equipment will be installed on the telescope as access is made possible during 1995.

The antenna control system software consists of two major components — the antenna positioning and pointing. During 1995, the major work emphasis will be on the antenna positioning system and will include controlling the subreflector, prime focus mirrors, feed rotator, and receiver turret.

VI. MAJOR NEW INITIATIVES

1. The Millimeter Array

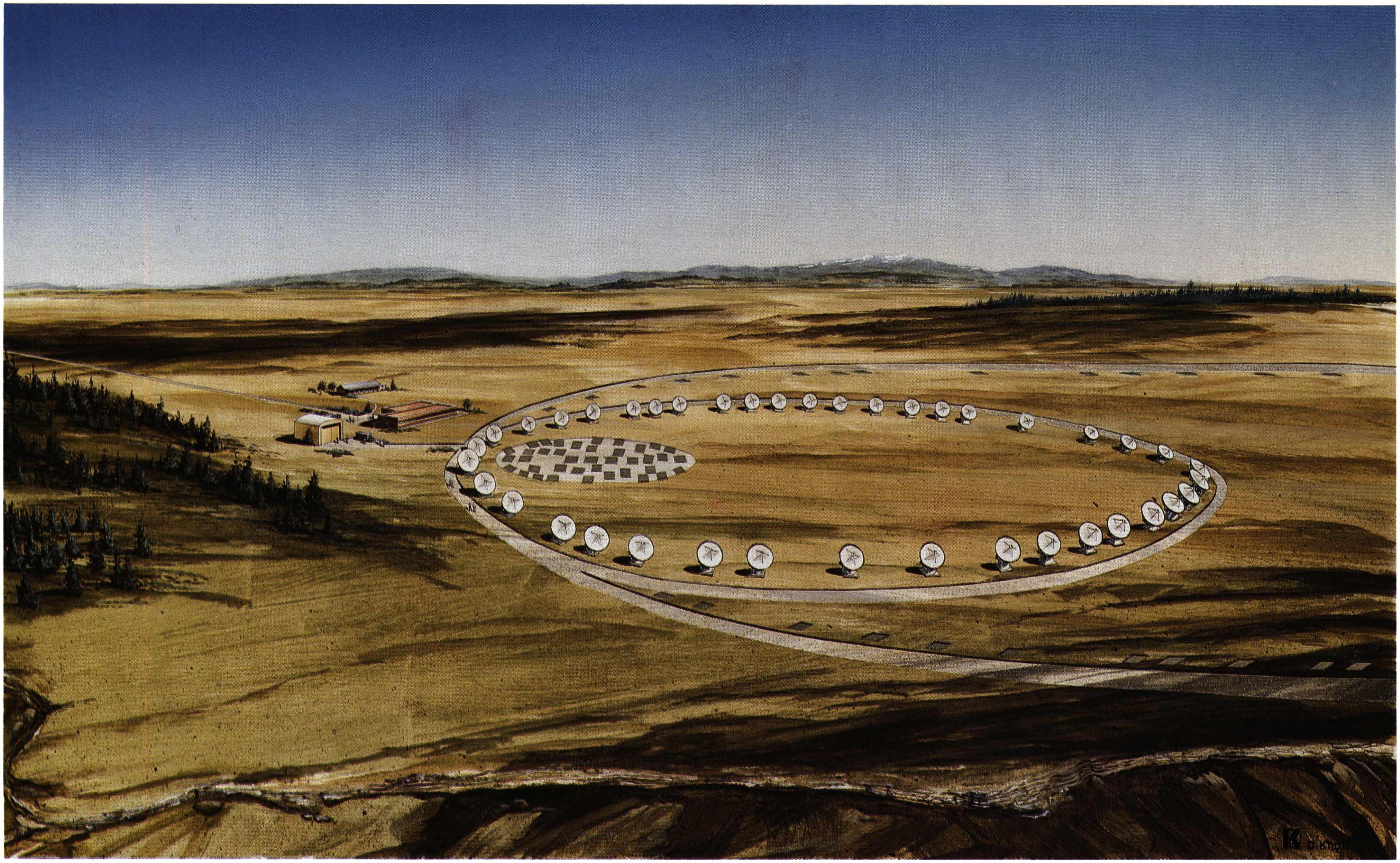
Design of the Millimeter Array began at the NRAO in 1983 and was assembled from the ideas of more than seventy astronomers at three scientific workshops held at the NRAO from 1985 to 1989. A formal proposal for the MMA submitted to the NSF in 1990 culminated this phase of the effort. The MMA was highlighted by the Astronomy and Astrophysics Survey Report (the "Bahcall Report") as one of the four major astronomical facilities for the decade of the 1990s.

The MMA is a high-resolution imaging array comprised of forty 8-meter transportable antennas located at a high altitude site. An artist concept of the MMA is shown as Figure 6. The Millimeter Array combines the sensitivity provided by the collecting area of a telescope 50 meters in diameter with angular resolution $<0''.1$, superior to that of the design goals of the Hubble Space Telescope, and it operates at frequencies 35-350 GHz at which thermal processes illuminate the sky. This unprecedented combination of sensitivity and angular resolution at short wavelengths will make available for astronomical investigation a wealth of unique opportunities and new science, including the ability to:

- Image the redshifted dust continuum emission and gas spectral-line emission from evolving galaxies at epochs of formation as early as z = 10;
- Reveal the kinematics of optically obscured galactic nuclei and QSOs on spatial scales smaller than 100 pc;
- Resolve the gaseous disks and reveal the chemistry of protostellar and protoplanetary systems;
- Reveal the isotopic and chemical gradients within circumstellar shells that reflect the chronology of stellar nuclear processing.

Recent Progress

Within the last twenty-four months, the NSF Advisory Committee for Astronomical Sciences gave its enthusiastic endorsement to the MMA and suggested that the Foundation proceed with a three-year research and development phase for the project. We were asked to provide the NSF with a plan for the MMA design and development; we presented the plan to them in September 1992. The plan describes all aspects of the technical and environmental/site work that needs to be accomplished to put us in a position to begin



THE MMA ARTIST CONCEPTION

NATIONAL RADIO ASTRONOMY OBSERVATORY - Operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

construction of the array. We have attempted to make the MMA Design and Development Plan comprehensive: the plan incorporates not only the work that must be done to develop the hardware needed by the array but it also highlights the need for us to develop techniques for hardware fabrication and testing that will enable us to produce multiple copies of the various components that have nearly identical performance characteristics.

In 1995 the MMA Design and Development Plan will be rewritten, recognizing the involvement of the U.S. university millimeter interferometer array groups in the development of the MMA through the MMA Development Consortium.

Site Evaluation

Four sites are under active investigation for the MMA, two in the continental southwest, the third on Mauna Kea on the island of Hawaii, and a fourth in northern Chile. A transportable 225 GHz site-testing radiometer has been operated for a year or more on the three U.S. sites, providing us with a measure for the millimeter-wave transparency and stability. In 1995 atmospheric transparency and stability measurements will also be made at the possible Chilean site.

Antenna Design

The MMA antenna is a highly precise reflector that must be capable of precision pointing and tracking when fully exposed to the environment. No existing antenna achieves the MMA performance specifications: existing high-precision antennas retain their precision by being sheltered from wind and sun in an enclosure. The MMA antenna must be transportable from one location to another, and hence it cannot be sheltered in a fixed structure.

To meet the MMA performance specifications, a novel design has been engineered employing innovative mount geometry, extensive use of composite materials, and clear aperture optics.

Gravitational distortion of the primary reflecting surface is the primary obstacle to meet the precision reflecting requirement of the MMA. The MMA antenna design overcomes this obstacle by a unique combination consisting of an offset reflector and a slant axis mounting. With this combination, the varying gravitational deflection is never perpendicular to the antenna surface, and the gravitational distortion is minimized in a way that is not possible with a conventional antenna design. Although the major consideration in developing this design concept has been reduction of gravitational structural distortions, the design also offers greatly reduced aperture blockage, increased rigidity, and low weight.

Thermal deformations as a result of sunlight shinning on one part of the antenna structure while other parts are shaded limits precision antenna operation in the daytime. Since the MMA will operate 12 hours a day, this obstacle also must be overcome. To do so, the MMA antenna design uses composite material, carbon fiber reinforced plastic (CFRP), for the truss structure that supports the primary reflector. CFRP can be manufactured with little or no expansion or contraction when heated. No ground-based antenna has yet been built by a U.S. manufacturer using composite materials. The MMA antenna design includes CFRP structure and fabrication as an integral element.

The offset optics, clear aperture, of the MMA antenna assures high performance for astronomical imaging by minimizing unwanted sidelobe response and permitting a very stiff support for the secondary mirror.

Design of the MMA antenna is quite advanced. Figure 7 shows the current concept. The novel combination of an offset reflector and slant-axis mount reduced gravitational distortions of the surface to less than one-tenth of what they would be in a conventional alt-azimuth design. The MMA antenna design meets the performance goals set for the array and does so with a simple, lightweight design.

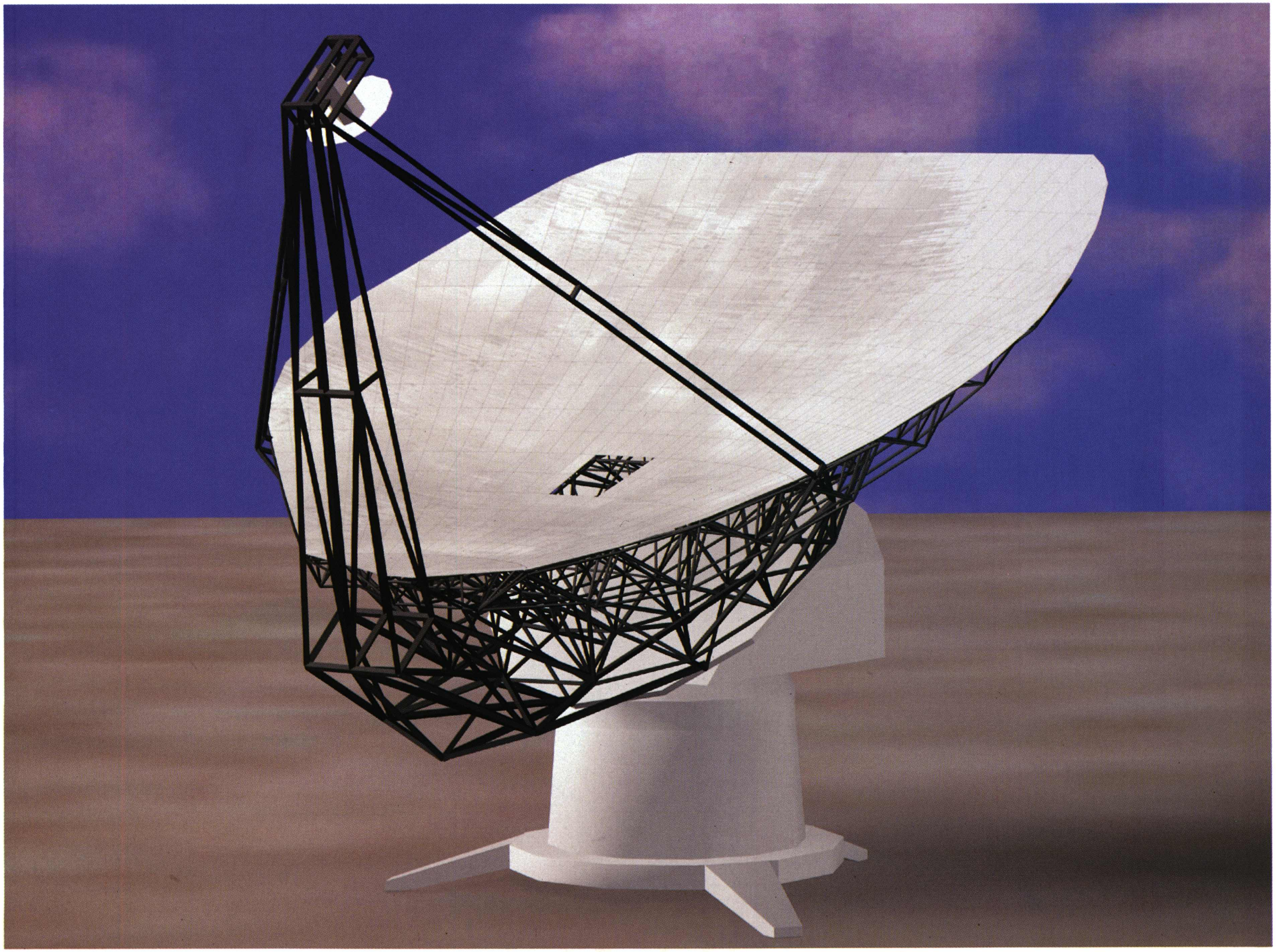
Receiver Design

The current generation of SIS mixer receivers now on the 12 Meter Telescope meet the performance specifications for the MMA receivers. They do so however with mechanical tuners. Progress on simple tunerless mixers for the MMA is coming along well at the NRAO (CDL); prototype 200-300 GHz tunerless mixers are now on the 12 Meter Telescope in the 8-beam receiver.

The first performance specifications for millimeter-wave, 60-80 GHz HFET receivers are also available from the CDL and look encouraging for the prospect of MMA HFET receivers throughout the 3 mm band.

MMA Development Consortium

Recognizing that the National Radio Astronomy Observatory, the Owens Valley Radio Observatory (OVRO), and the Berkeley-Illinois-Maryland Association (BIMA) share a common interest in promoting the development of the Millimeter Array, in assuring that students and postdoctorals have continued access to a facility for astronomical instrumentation development and research at millimeter wavelengths, and in enhancing the spirit of collaboration between university groups and the national observatory, the three organizations have agreed to establish the Millimeter Array Development Consortium (MDC).



THE CURRENT MMA ANTENNA CONCEPT

NATIONAL RADIO ASTRONOMY OBSERVATORY - Operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation

The MDC will provide overall guidance for the development phase of the Millimeter Array. The MDC will be managed by an Executive Committee of four members, two representatives from the NRAO and one each from OVRO and BIMA, appointed by the participating institutions. It will be the role of the Executive Committee to define the development tasks, identify personnel to work on the tasks, and assign to the tasks any funds made available by the NSF specifically for the activities of the MDC. The Executive Committee will also coordinate activities and communicate progress to all participants.

It is the expectation that the MMA Development Plan, to be revised by the MDC, will involve the specification of MMA instrumentation through development and prototyping of instrumentation on the OVRO and BIMA antennas. We anticipate that the concept of a university-based development array for development of the national MMA is a concept that can be extended with benefit throughout the operational phase of the MMA. In addition, it is a concept that could serve as a new model for future large science projects where there is a desire to maintain viable university-based instrumentation development efforts.

Construction Cost of the MMA

In the MMA proposal submitted to the NSF in 1990, the construction cost of the MMA on a continental U.S. site was estimated to be $120M in 1990 dollars. In dollars of 1995, inflation alone would make the 1990 figure escalate to approximately $140M. Now that the antenna design is mature and we have built the type of SIS receivers we expect to use on the MMA, we can cost the major items of the array with much greater precision than was possible in 1990. Currently we anticipate a cost of $150M in 1995 dollars for the array in the continental U.S.; that is, our current estimate is basically unchanged from our 1990 estimate in dollars of the same year. If the array is built over several years, as it must be, and inflation is taken into account, the MMA construction budget is estimated to be approximately $175M. Construction in Chile or in the Hawaiian Islands will increase the cost by about 15 percent.

MMA Advisory Committee

A MMA Advisory Committee has been appointed to provide continuing advice on all aspects of the project to the NRAO Director. The Committee meets at least once annually and shares with the MDC the responsibility for recommendations on all major decisions affecting the array. The membership of the Committee is shown in Appendix D.

The initial meeting of the Advisory Committee was in September 1993. The emphasis of this meeting was on the site evaluation process, antenna design work, and receiver development efforts. Some of the work recommended by the Committee has been done and is included in the discussion above. The Advisory Committee is to meet again November 18, 1994, to review the work of the MDC in constructing the MMA Development Plan. When the NSF makes available specific funds for the MMA Development work, the Advisory Committee will be expanded and it will meet more frequently.

2. VLA Upgrade

Overview

The VLA upgrade was described in Section IV. It has four key elements:

- Design and construct a new correlator to process both broadband continuum signals and to provide improved resolution and flexibility for spectral-line work.
- Replace the buried waveguide with a fiber-optics data transmission system.
- Replace most of the VLA receivers to achieve lower noise temperatures and a much wider bandwidth, and add two new observing bands.
- Improve pointing, surface accuracy, and ground pickup as necessary complements to the upgrades.

Several of the VLA systems might be used with little or no change. For example, the antenna drive system could be adopted with little change. The time-keeping equipment should not require upgrade. The only change in the infrastructure would be installing the fiber-optics cable and abandoning the waveguide. The required cryogenic capacity is already in place.

The impact of these improvements will be enormous. The continuum sensitivity of the instrument will improve by as much as an order of magnitude, new and powerful spectral observations will be possible, and new areas of the radio spectrum will be opened for exploration. These improvements will allow the VLA to retain its status as the premier aperture synthesis telescope for radio astronomy well into the next century.

Cost and Schedule

A fundamental requirement of the upgrade project is that the VLA should continue to function as a user instrument during the upgrade. The impact of this on cost and schedule is uncertain. Nonetheless, some estimates can be made.

The time scale of the project will probably be set by the need to move antennas through the antenna assembly building for the antenna upgrade. The tasks will include:

- New feed cone and receiver installation.
- Antenna surface improvements.
- Possible azimuth bearing replacements (~1 out of every 5 antennas).
- Normal preventive maintenance and retrofits.

Allowing eight weeks per antenna to overhaul four of every five antennas, and assuming the fifth antenna will require a twelve-week overhaul (azimuth bearing replacement), approximately five antennas could be overhauled per year. This gives a time scale for the project of six years. During that time there will often be two antennas out of the observing array for upgrade. An illustrative project budget is given in Table VIII, the total cost being of order $33M.

Table VIII. VLA Upgrade Budget Estimate

		M&S ($k)	Wages ($k)	Man-Year
1.	Receivers	6150	2300	50
1a.	Feeds	1050	50	2
2.	Antenna LO/IF	3000	1750	60
3.	LO/IF Transmission	2400	100	
4.	Central LO/IF	1600	900	30
5.	Correlator	5600	1000	20
6.	Hardware	400		
7.	Ant. Mechanical	900	800	18
8.	Test Equipment	150		
		21250	6900	182
	Benefits on Wages 30%		2070	
	Contingency 10% (M&S and Wages)	2100	680	
		23350	9650	
	Total	33000		

3. VLA-VLBA Connection

A plan to bridge the gap in angular resolution between the maximum achievable by the VLA, ~0."1, and the minimum provided by the VLBA, ~0."0.1, was endorsed by the report of the Astronomy and Astrophysics Survey Committee as one of the recommended moderate programs. Connection of the two arrays will increase the resolution of the VLA at all frequencies; improve the dynamic range, field of view, and extended source sensitivity of the VLBA; and give a scaled array capability at 0."1 resolution for all frequencies from 300 MHz to 22 GHz.

The VLA/VLBA connection will be accomplished with a phased plan which includes the following three steps:

- Placing four VLBA recorders at the VLA so that the antennas at the ends of the wye arms can be used as independent VLBA telescopes;
- Constructing four new VLBA antennas (at Dusty, Bernardo, and Vaughn, New Mexico and at Holbrook, Arizona) for measurement of short VLBA spacings;
- Providing fiber-optic links from the VLA to the four new antennas as well as to the VLBA antennas at Pie Town and Los Alamos. These six outrigger antennas would then be used as part of the VLA. The VLA correlator will be expanded from 27 to 33 stations to accommodate the additional baselines.

Together, these improvements will provide a greatly enhanced imaging capability and brightness sensitivity over a wide range of frequency. The scientific applications will include observations of the sun and planets, radio emission from stars, novae, proto-planetary nebulae, and stellar winds, as well as from star-forming regions, active galactic nuclei, and quasars. The VLA/VLBA connection is a long-term goal of the Observatory; the details of realizing this goal, and the cost involved, are still to be worked out.

VII. NON-NSF RESEARCH

1. United States Naval Observatory

The year 1995 will be one of transition for the United States Naval Observatory operations at Green Bank. A new 20-meter antenna will be completed that will enter service as part of the NAVNET system which uses VLBI techniques for earth orientation measurements. The NAVNET telescopes make VLBI observations to provide fundamental data on earth rotation and pole location needed for the USNO's fundamental interest in timekeeping. These data are also essential to the analysis of observations from the VLA and VLBA as well as other uses. For a number of years the NRAO has operated an 85-foot telescope in Green Bank for the USNO VLBI network. When the new 20-meter antenna is completed, it will be operated in conjunction with the 85-foot telescope until it is established that the new antenna is performing satisfactorily. At that time the 85-foot telescope will be taken out of service and USNO operations will be switched entirely to the 20 meter. The new antenna will have a new, more sensitive and stable front-end, a higher aperture efficiency, and greater sky coverage and slew rates than the 85-foot telescope it will replace.

In 1995 work will begin on an addition to the Jansky Lab that is funded by the U.S. Navy to support USNO operations in Green Bank. The addition will have space for the USNO 20-meter control room and VLBI facilities, and offices and labs for engineers, operations personnel, and scientists associated with the USNO activities. The building addition will also contain a small auditorium, offices, and other facilities that will be of general use to the Observatory.

2. NASA-Green Bank Orbiting VLBI Earth Station

By the beginning of 1995, the OVLBI Earth Station project will have completed its construction phase and will have started its interim operations phase. The latter continues until several months before the launch of the first supported satellite, now expected to be VSOP in late 1996, followed by Radioastron in early 1997. We then enter the full operations phase and carry out routine tracking and data acquisition activities throughout the scientifically useful lives of the two satellites.

During the interim phase, we will concentrate on detailed testing of the hardware and software, including the critical testing of interfaces to other mission elements that could not be done during the construction phase. Compatibility tests with Russian and Japanese flight hardware will be important for establishing the functionality of the station. We will also continue with hardware and software development at a low level. This will allow us to keep up with any changes in mission requirements or spacecraft designs, as well as to address any problems that show up in the detailed tests. Finally, we will attempt to track any satellites that are in accessible orbits and are transmitting in the supported bands. In particular, we will track the SURFSAT transponder that is planned specifically to test the OVLBI time transfer and orbit determination techniques. SURFSAT is scheduled for launch in March 1995.

3. NASA-OVLBI Science Support

The NRAO Space VLBI Project, based at the Array Operations Center in Socorro, New Mexico, includes the NRAO activities funded by NASA through the U. S. Space VLBI Project at JPL, in support of the international space-VLBI missions Radioastron and VSOP. The scope of the project was reduced significantly in 1994 as a result of NASA budget constraints. It now comprises the following tasks:

Management and Science

This activity, which will continue throughout the duration of the project, involves management and scientific oversight by NRAO personnel with respect to project goals, implementation plans, and progress. Since both space-VLBI missions are international in scope, frequent interactions will be necessary to maintain coherent interfaces with other mission elements. NRAO personnel are members of the two international scientific councils which serve as steering committees for the two missions.

VLBA Correlator Enhancements

Modification of the VLBA correlator to support space-VLBI observations will continue. Tests of the expanded delay-rate capability will be completed. Spacecraft ephemeris software, imported from JPL, will be incorporated into the correlator's operational environment. Additional software to accept and interpolate phase-transfer-link correction data will be written and tested. Finally, the plan resulting from a current study of trade-offs between the correlator's output data rate, and the accuracy of spacecraft orbit determination, will be implemented.

AIPS Enhancements

Further enhancements of the baseline oriented fringe-fitting tasks, BLING and BLAPP, will be developed. Most important among these is the capability to let the parameter windows track results already obtained, both forward and backward in time. An initial version of an interactive source model-fitting task will be completed and tested.

User Support and Operations Support

Activity in these areas will be limited primarily to preliminary planning. The first user support staff member should also be hired to ensure adequate training can be completed before launch of the first space VLBI mission.

VIII. EDUCATION PROGRAM

With observing sites and scientific offices located in ten states and the territory of the U.S. Virgin Islands, the NRAO has a public visibility that is being exploited to further science awareness and science education. Formal education in the form of supervised research experiences with the NRAO radio telescopes is provided to professional and pre-professional scientists. Programs that emphasize how scientists work and what they hope to accomplish are provided to secondary science teachers and interested amateur astronomy groups. Finally, public educational activities are sponsored at all the NRAO observing sites in the form of guided and self-guided tours, public access to the images of objects in the radio sky, and descriptions of the nature of objects studied by radio astronomers. A few of the highlights of the NRAO educational program are summarized below.

Professional and Pre-Professional Education

Postdoctoral Fellows

At the NRAO postdoctoral appointees are given Jansky Postdoctorals with a term of two years that may be extended an additional year. In the selection process recent graduates are given preference to those who are applying for their second postdoctoral position. In principle, Jansky Postdoctorals are available not only to those in radio astronomy but they are also available to recent Ph.D. recipients in engineering and computer science.

Postdoctorals at the NRAO are encouraged to define their own research program; they are not asked to serve as apprentices to NRAO staff scientists. The purpose of the program is to provide an opportunity for young scientists to establish their research credentials so that they may more effectively compete for permanent positions and become themselves better teachers of, and researchers in, radio astronomy. Approximately ten Jansky Postdoctorals are in residence at the NRAO at any time; the term of their appointment is three years.

Resident Ph.D. Thesis Students

As astronomy becomes a more phenomena-oriented discipline, and less divided by observing wavelengths, radio astronomical observations play an important role in a wide variety of astronomy Ph.D. theses. Some of the universities awarding degrees in astronomy have few, or no, radio astronomers to guide student research in radio astronomy. To rectify the situation and train students in the techniques of radio astronomy specifically needed for the individual student's research, the NRAO staff scientists collaborate with university astronomers in the supervision of Ph.D. thesis students. The students spend as long as twenty-four months in residence at the NRAO taking data, reducing it, and writing their theses — all with the guidance of NRAO staff scientists.

Presently there are eight resident Ph.D. thesis students at the NRAO doing research in astronomy, microwave engineering, and computer science. This program principally benefits the student, but it has a salutary effect as well for the NRAO staff supervisor.

Non-Resident Ph.D. Thesis Students

More than 125 Ph.D. thesis students use the NRAO facilities each year for their research. While these individuals receive no direct salary support from the NRAO, their stay of one to a few weeks at the Observatory is supported directly by a housing subsidy (in Socorro), travel reimbursement, computer time, and supplies; and it is indirectly supported by assistance from the NRAO scientists and staff as needed. Many of the students using NRAO facilities this year will receive their introduction to radio astronomy from NRAO staff scientists.

Summer Students

For thirty-five years the NRAO has offered summer appointments to students interested in broadening their exposure to radio astronomy. Many of the former NRAO summer students are now established researchers. In this sense the summer student program has been very successful indeed.

One of the strengths of the early program was its emphasis on students who had made a commitment to radio astronomy: the only students admitted to the program were graduate students in radio astronomy, engineering, or computing. One of its weaknesses was that it was funded out of contract funds and, when funding was tight, the program was constrained. In 1982 there was no summer student program at all.

In 1987 the NSF funded a program for summer student research opportunities called Research Experiences for Undergraduates (REU). The NRAO has applied for REU funds every year since 1987 and has annually supported eighteen to twenty summer students from these funds. All these students are, of course, undergraduates and as such have not made a commitment to radio astronomy nor do they, usually, have the research skills of graduate students. Many students are exploring radio astronomy as a career option; others are simply looking for summer employment.

Each year since 1987 we have supplemented the REU funds with funds from the Cooperative Agreement to support a few graduate students, bringing the total number of summer students to nearly thirty. Approximately half this number are astronomy students; the remainder are interested in the engineering and computing aspects of radio astronomy.

Through exposure to hands-on research, we hope to persuade the summer students to strengthen their commitment to careers in science.

In addition to the REU summer students there are students working at the NRAO from other institutions. During the summer months students not supported by the NRAO REU program come from other institutions at their own expense to work with the NRAO scientific staff and to participate in the NRAO student program. We expect a steady growth in the summer student program through the period of the Long Range Plan.

Scientific Workshops and Symposia

Green Bank Workshops

NRAO has traditionally hosted symposia and workshops on special topics of interest to research astronomers, those who develop new instrumentation, and their students. The series of Green Bank workshops are well-known: twenty workshops on topics from "Phases of the Interstellar Medium" to "Large Scale Surveys of the Sky" have been held to date. We anticipate a continuation of this series during the period of the present plan that will accompany bringing the GBT into operation.

Synthesis Imaging Workshops

One important measure of the success of the VLA is the number of scientists who use the telescope each year, viz, more than six hundred. That so many people could use it speaks to its operational ease and convenience. At the same time sophisticated users seek to push the VLA to its limits; they recognize that one needs to understand its subtleties in order to do so. We attempt to communicate this information to users, particularly student users, by workshops held in Socorro on synthesis imaging.

Synthesis imaging workshops are held every three years. More than 115 students (mostly graduate students) attended the most recent workshop, the third in six years. Thirty-one NRAO staff scientists developed the theory and application of aperture synthesis in various lectures that were given over a ten-day period. The proceedings of all the workshops have been published. We expect this series to continue.

The VLBA promises to make VLBI readily accessible to the large number of users accustomed to observing with the VLA. In order to accelerate the process, the NRAO focussed the recent synthesis imaging workshop on the techniques of VLBA imaging. Thirty-one lectures were presented by 24 lecturers. About 100 graduate students and others attended for approximately ten days. We expect to sponsor synthesis imaging workshops in the future that highlight both VLA-related and VLBA-related imaging theory and practice.

Tucson Scientific and Technical Meetings

In the last few years, the NRAO in Tucson has hosted a number of international, specialist scientific and technical workshops. These have been well attended by the leading world authorities in the respective fields as well as representatives from high technology industries. In 1992 a workshop was held on "Remote Observing," hosted jointly with the Royal Observatory, Edinburgh (ROE). The proceedings of this workshop have been published by World Scientific Publishing. In 1993 a specialist workshop on "Next Generation Digital Correlators" was held. Proceedings of this workshop are available from NRAO in Tucson. Also in 1993, NRAO sponsored jointly with Steward Observatory a symposium, in "Infrared Cirrus and Diffuse Interstellar Clouds." The proceedings of this symposium are to be published in the ASP Conference Series. In May of 1994, NRAO Tucson hosted an international workshop on "Multi-feed Systems for Radio Telescopes;" proceedings will be published also in the ASP Conference Series. For 1995, a major scientific symposium is planned, commemorating the fifteenth anniversary of the discovery of the CO molecule with the 12 Meter Telescope, then known as the 36 Foot. The CO symposium will be co-sponsored by the IAU as IAU Symposium 140.

Public Education

Images of Radio Astronomy

The NRAO maintains a collection of slides illustrating the telescopes, techniques, and research images of radio astronomy. These slides are made available to students, classroom teachers, professional colleagues, and the media. In 1993 we expanded this outreach program by issuing a compact disk of more than 3500 astronomical images, called "Images from the Radio Universe." These images can be displayed on a PC computer screen and manipulated by students seeking to explore radio astronomy from their classroom. Each of the images is fully documented and calibrated — they are not "toys" or illustrations. These are research quality images in every respect.

Work will continue in the next year on a similar collection of radio images made of the complete third Cambridge catalog of radio sources. This collection will include images from the VLA, MERLIN, and the Westerbork synthesis telescope. As a collection meant for students as well as professional colleagues, all these images will again be complete, documented, and available as a compact disk for personal computers and workstations.

Green Bank Educational Program

General Public Tours

About 20,000 visitors yearly. The tour season begins on Memorial Day and lasts through the end of October. From Memorial Day through mid-June and from Labor Day through the end of October, tours run on weekends only. During the rest of the season, tours run daily. Three tour guides are hired for the season. They are college students, science, engineering, or science education majors.

A tour consists of an introductory talk given by the guide, a slide show, and a bus tour of the telescopes. In addition, the guides offer demonstrations of lasers and retro-reflectors, cryogenics, and superconductivity. The guides assist school groups in using small radio and optical telescopes.

Science Teachers Institute (in partnership with West Virginia University). Two 2-week programs a year for science teachers from around the country. Thirteen institutes have been successfully completed since 1987; 327 teachers have participated. While at the NRAO, participants investigate problems using the 40 Foot Radio Telescope, receive lectures on general astronomy and on current research in radio astronomy, build a scientific instrument to use in the classroom, and participate in education discussions and activities. This program requires much participation from NRAO staff as lecturers during the day and evening, as hosts during in-depth tours of all of the facilities, and as advisors to small and large groups of participants.

Participants have academic year duties as well. They must host four workshops for teachers in their home state and develop and implement project-based units with their students. The number of teachers indirectly benefitting from our institutes is estimated at 15,000. It can be estimated that over 100,000 students have benefitted from our institute program over the past seven years as well, using an average of four classes of 21 students/teacher/year.

National Youth Science Camp (NYSC)

Two graduating seniors are chosen from each state in the country to participate in the NYSC. During their three-week stay in West Virginia, they explore many topics in science. They attend lectures given by practicing scientists, take tours, and also study some topics in depth. These in-depth investigations are called Directed Studies. Small groups of campers, typically 10-12, are allowed to participate in a given Directed Study. NRAO offers two overnight directed studies at the 40 Foot Telescope. The campers are given operating instructions and access to our library before they begin their overnight. They usually decide for themselves what they wish to do. Usually they embark on several observing projects, with smaller groups working on each one. We also give the entire delegation a tour of the Observatory.

Since its beginning in 1962, the National Youth Science Camp has served about 3000 students. NRAO has been involved, sometimes to a much greater extent than outlined above, with all of these students.

U.S. Department of Education Science and Math Initiatives

This is part of a program offered by Frostburg State College, Glenville State College, and Fairmont State College. Each sponsored program exposes about 40 disadvantaged high school students to different areas of science. NRAO is one of several science institutions that has participated in these projects (to the largest extent with Glenville State College). We have offered in-depth tours, interviews with scientists, and observing at the 40 Foot. As part of the Glenville State College Project, one of our staff scientist acted as advisor to a small group of students who decided to do astronomy projects during the school year. Some of their projects involved remote use of the 40 Foot Telescope.

Extended Visits

Small groups of students use the 40 Foot. These groups come from colleges, Governors' Honors Academies, gifted programs, and classroom teachers who have participated in our institutes or chautauqua programs. These visits occur in summer and throughout the school year. Their stays range from several hours to a week. While at NRAO, students may ask to speak to a scientist or to take an in-depth tour of the 140 Foot or Green Bank Telescope site. Before visiting for an extended observing run, students must submit an observing proposal which models 140 Foot observing proposals in form. Included is a list of all extended educational visits from 1990 through 1994. A total of 8356 people were served during that time period.

Society of Amateur Radio Astronomers (SARA)

SARA holds its annual conference at Green Bank. Members gather to share information on home-made radio telescopes, receivers, data logging software, etc. They receive technical advice and assistance in calibrating their components from NRAO engineers while on site. SARA is committed to sharing their knowledge with others, particularly teachers and students. Our assistance to them is repaid through the educational efforts of SARA.

Hands on Science (HOS)

This program, developed by a nonprofit parent/teacher group in Maryland, consists of after-school "recreational" science activities in one, one-hour session each week (eight weeks per class). The program was offered to K-6 grade students. The program is currently being offered at the local elementary school. Many of the class leaders have been NRAO employees: engineers, scientists, and technicians. The program is coordinated by the NRAO education officer in Green Bank. We have offered HOS for three years and expect to continue in the future.

School Group Tours and Extended Visits

School group tours can be arranged throughout the school year. The tours are customized as much as can be according to the grade level of the students, student interests, the length of time they wish to spend at the Observatory, and so forth.

Elderhostel

This is a one-week program for groups of 25-30 older adults co-hosted by Glenville State College and the NRAO. The program is held in Green Bank. NRAO provides lodging, tours, a talk or two, and instructions on 40 Foot Telescope use. The hostelers use the 40 Foot under the guidance of Glenville State College staff. Glenville State College staff provide the general astronomy instruction.

Chautauqua

This is a three-day intensive workshop for professors of small colleges. Traditionally, these professors are not active in research. The chautauqua is a way for them to update themselves in current science and technology. The caduca requires the participation of several of our staff. Astronomers and engineers offer lectures on science, the GBT, how receivers work, while others lead the group in in-depth tours of the Observatory. The participants also receive instruction on the use of the 40 Foot. Several initiate 40 Foot Telescope observing projects with their students; some return to Green Bank, others use the telescope remotely. The caduca program has been supported for six years; thirty professors participate each year.

Remote Access to NRAO

Access to 40 Foot Telescope data is now possible through Internet. Teachers, precollege students, and undergraduate students have requested observing time, sent observing programs, and retrieved 40 Foot data via e-mail. Scientists have also been contacted by students through the Internet, most formal through the Science by E-mail program. Marshall University (Huntington, WV) is spearheading this program for five science classrooms in rural southwestern West Virginia.

Socorro Educational Program

The VLA Visitor Center, opened in 1983, hosts at least 15,000 visitors annually. These visitors come year-round from throughout the United States and from around the world. Comments written in the center's sign-up book indicate that for many tourists the VLA is a specific, planned stop on their trip. Many tourists call or write NRAO well in advance of their trip to obtain information about visiting the telescope.

The visitor center features an automated slide show with audio narration, displays on the history of radio astronomy, the operation of the VLA and VLBA, and rotating displays on scientific results from the VLA and VLBA. The visitor center is the starting point for a self-guided walking tour of the central portion of the VLA site. A free brochure provides background information for visitors making the walking tour. Signs at stops on the walking tour explain the components of the VLA visible from each stop. The walking tour provides visitors with close-up views of an antenna, the antenna assembly building, the transporter vehicles, and, from an outdoor balcony on the control building, views of the VLA's electronics and control rooms.

Though the visitor center is not staffed, we provide regularly scheduled guided tours on summer weekends, using NRAO summer students as guides. Throughout the year, by appointment, we provide staff tour guides for school groups and other organizations. The number of such guided tours averages about 35 annually.

Future plans for the VLA Visitor Center focus on two main themes: evolving and improving the displays and providing staffing for the center.

Displays at a facility such as our visitor center must constantly evolve to reflect continuing technical and scientific developments. We are looking beyond that normal evolution, however, to improve the methods used to convey information to the public. One aspect of this improvement is to incorporate more hands-on or interactive displays. During 1994, we plan to install a working microwave radiometer sensitive enough to detect the radio flux from a person's hand placed over its feedhorn. We are exploring other ideas for active exhibits. The visitor center currently includes two videotape playback setups, and we hope to produce new program material for these. In addition, we are investigating ways of using inexpensive personal computers to display recent scientific images and explanatory text, possibly interactively, to visitors.

The long-term evolution of the visitor center displays will necessarily involve interaction with professionals at museums and other observatories. We want to keep abreast of technology available for education as well as of newly developed techniques for successfully imparting the excitement of science to the general public.

While visitor comments indicate that the self-guided tour is a well-liked feature, we know that a knowledgeable guide makes the visitor's experience significantly more informative and rewarding. Many of those who receive a guided tour tell us that they previously did the walking tour, but greatly appreciated the subsequent chance to hear explanations and to ask questions of a guide. Personal interaction with visitors also provides feedback on the effectiveness of the displays and on areas where visitors have questions and possible misunderstandings about astronomy. Our year-round, by-appointment tour program has been reaching schools throughout New Mexico and surrounding states, but is now operating at about the maximum capacity we can handle without staff members dedicated to this purpose. With staffing for the visitor center, we could publicize this service more widely and reach many more schools. In addition, we could initiate daily tours at a specific time or times, advertise this fact, and allow tourists to plan their visits to take advantage of this feature.

For these reasons, we are exploring ways of providing full-time staffing at the VLA Visitor Center. We see two primary methods of doing this. The first would be to obtain funding to staff the center with full-time employees. We are exploring programs at the national and state level that might support this. The second alternative is to recruit and train volunteers for this purpose. Using volunteers would still require staff time for training, supervision, and coordination, and would require resolving questions about liability, transportation, and other logistical aspects. We are exploring the feasibility of using volunteers recruited from either the public at large or from various organizations, such as amateur astronomy groups.

The two staffing models outlined above are not necessarily exclusive. A small full-time staff could be used as a core of expertise and for the required oversight and coordination, and their effect greatly multiplied through the use of volunteers. A phased approach to staffing the visitor center may prove the best way of accomplishing this goal, and NRAO is examining these alternatives.

Both in Socorro and at the VLBA sites, NRAO staff members frequently give lectures in schools and to local organizations. Some area teachers regularly use NRAO staff members as guest speakers, and we attempt to make the availability of our staff well known to the schools. NRAO provides a display and staffing for career days at local schools, a particularly important function in a region where there are large numbers of minority and disadvantaged children who need to be made aware of the possibility of scientific or technical career paths.

We have prepared a pamphlet aimed at educators which outlines the NRAO services available to them. In this document, we offer tours, speakers, literature, and the assistance of our staff in serving as a resource for information about science, engineering, and computers. This has been distributed to groups of teachers visiting Socorro and at the 1994 Socorro Consolidated Schools annual pre-service training session. Copies of this have been mailed to science coordinators at the larger school systems in New Mexico and to the State Department of Education.

NRAO is ideally positioned to use the amateur radio community as a force multiplier for public education efforts. As would be expected, many of our staff members are radio amateurs and are involved in local and national radio organizations. Staff members present lectures at amateur radio organizations, and NRAO has provided displays on radio astronomy at amateur radio events. We also have expanded our contacts with amateur radio publications, with the result that several articles on NRAO scientific results and technical developments have appeared in national publications over the past year. A recent example is coverage of the availability of NRAO VLA Sky Survey maps via the internet in QST, the most prestigious of the amateur radio magazines. We anticipate that our increasing exposure among radio amateurs will result in more opportunities to promote radio astronomy through tours and lectures.

Tucson Education Program

NRAO staff scientists in Tucson continue to work closely at all levels with Steward Observatory, at the University of Arizona. NRAO scientists already help with supervision of graduate students, but in the near future will also become more involved with student education. Lectures on astronomical techniques will be given jointly by NRAO and Steward Observatory staff.

The 12 Meter Telescope is included in the special tours done by Kitt Peak National Observatory in connection with their monthly Public Nights. About fifty people visit the 12 Meter on each of these occasions. Many special tours of the 12 Meter Telescope are arranged upon request throughout the year. The participants range from groups of professional engineers to amateur astronomers and interested members of the public. There is a model of the 12 Meter Telescope and other material displayed prominently at the Kitt Peak Visitors' Center, which is visited by 80,000 each year.

VLBA Sites

Several of the VLBA stations are either prominently visible or well-known in their local communities. These stations are visited by a significant number of people each year. Though these stations are minimally staffed, the on-site technicians have provided information and guided tours to numerous groups, including school classes, amateur astronomers, amateur radio groups, and professional engineering organizations. NRAO has prepared an informational brochure on the VLBA, and each station is provided with a stock of these brochures for distribution to visitors. Each station also is provided with a set of slides and book of caption information to assist the site technicians with their presentations to the public. As the VLBA ramps up to full operation, we will expand efforts to keep the site personnel aware of the scientific achievements of the VLBA to assist them in their presentations. At each VLBA station, NRAO has erected an informational sign describing the purpose of the instrument for interested passersby.

Two VLBA stations are located near major optical observatories, at Kitt Peak, Arizona, and Fort Davis, Texas. At these locations, NRAO works with their visitor centers staff to provide information on the radio telescope at their site and on radio astronomy in general. NRAO is working with the NOAO staff to produce a new display on radio astronomy for their Kitt Peak visitor center.

IX. 1995 PRELIMINARY FINANCIAL PLAN by Budget Category

(NSF Funds, $ in thousands)

	New Funds	Uncommitted Carryover of 1994 Funds	Total Available for Commitment	Commitments Carried Over from 1994 Funds	Available for Expenditure
Operations					
Personnel Compensation	$17,773		$17,773		$17,773
Personnel Benefits	5,510		5,510		5,510
Travel	659		659		659
Material and Services	7,355		7,355	700	8,055
Management Fee	660		660		660
Common Cost Recovery/ CDL Device Revenue	(635)		(635)		(635)
Total Operations	$31,322	$ 0	$31,322	$700	$32,022
Research and Operating Equipment	500	0	500	0	500
Total NSF Operations	$31,822	$ 0	$31,822	$700	$32,522
Design and Construction					
GBT	0	4,000	4,000	15,000	19,000
TOTAL NSF PLAN	$31,822	$4,000	$35,822	$15,700	$51,522

IX. 1995 PRELIMINARY FINANCIAL PLAN
by Function/Site

(NSF Funds, $ in thousands)

	Personnel	Salaries, Wages, and Benefits	Materials, Supplies, and Services	Travel	Total
Operations					
General and Administrative	28	$ 1,720	$ 988	$ 121	$ 2,829
Research Support	56	4,518	894	271	5,683
Technical Development	23	1,444	128	19	1,591
Green Bank Operations	80	4,074	500	25	4,599
Tucson Operations	26	1,592	537	34	2,163
Socorro Operations	207	9,935	4,308	189	14,432
Management Fee			660		660
Common Cost Recovery/					
CDL Device Revenue			(635)		(635)
Research and Operating Equipment			500		500
Total NSF Operations	420	$23,283	$7,880	$659	$31,822

APPENDIX A - NRAO SCIENTIFIC STAFF ACTIVITIES

There are 80 individuals with Ph.D. degrees at the NRAO. Most of the 80 are astronomers, some are engineers, and some are computer science professionals. All of these people include a strong research program as one important component of their Observatory responsibilities. In carrying out their tasks these individuals see ways to enhance the observing equipment, to streamline observing techniques, and to improve the software. They take the opportunity to do so by conducting challenging observations or otherwise experimenting within the bounds of a competitively reviewed observing program. In so doing the NRAO staff scientists develop a proficiency with the instruments and data analysis procedures that can be communicated to NRAO users. This has been, and continues to be, an effective mechanism to expand the horizons of radio astronomical research.

The specific astronomical research planned by the NRAO scientific staff in 1995 is summarized below by area of research.

1. Sun and the Solar System

Studies of solar flares at radio wavelengths provide information about where and when electrons are heated and accelerated in the solar corona, and how the energy contained in energetic electrons is subsequently transported within the flaring volume. They also constrain the magnetic field topology in the solar corona. Work in this area will proceed along several lines.

First, the earliest stages of the impulsive phase of solar flares remain unclear. Within a matter of seconds, enormous amounts of energy are liberated, a large fraction of which goes into heating and accelerating electrons. High-resolution microwave imaging offers a means of pin-pointing the energy release site and of following the evolution of the source in the critical early stages. Previously, the time resolution of available instrumentation was too low to accomplish this goal. Recent improvements to the VLA will allow us to obtain snapshot images of solar flares in two bands (and in both senses of circular polarization) five times per second.

Second, the question of what processes transport energy throughout the flaring volume is unclear. A detailed study of the dynamics of microwave sources will begin. High-resolution microwave imaging observations have shown that microwave solar burst regions are highly dynamic. Signals appear to propagate across magnetic neutral lines at roughly Alfvenic speeds. Are these effects indicative of transport processes, or are they the result of the interaction between the evolution of the electron distribution function and the magnetic field gradients? The related issues of the energy release site and energy transport will be studied in detail during the coming year. A number of high time resolution and high angular resolution observations of solar flares by the VLA will form the observational basis of this study.

Finally, the details of energy release during the course of a solar flare remains controversial, the question being whether or not the release is "fragmentary," with a flare being nothing more than a superposition of hundreds or even thousands of elementary acceleration events. In order to explore this issue, two data sets have been obtained. The first data set was designed to explore the smallest radio bursts detectable by the VLA, the so-called radio microbursts, in order to characterize their properties and their relation to hard x-ray microflares. A second data set, which has been accumulated annually for the past three years, has been to use the VLA to image decimetric bursts simultaneously with a broadband spectrometer. This series of observations has produced a rich archive of joint imaging and spectroscopic observations of decimetric bursts, including type III bursts, type U bursts, spike bursts, and type I bursts. Type U and decimetric spike bursts have not been imaged previously. During the next year attention will be given to the long-standing problem of the origin of type I bursts and noise storms.

The research described above all involves study of solar bursts; equally interesting however are questions involving the structure of the quiescent solar atmosphere.

One of the outstanding problems of solar physics has been a detailed understanding of the sun's outer atmosphere. The VLA allows us to image radio emission from the corona, transition region, and upper chromosphere. Of particular interest is the structure of solar active regions, the site of enhanced magnetic field and of solar flares. A comprehensive data set involving high resolution, multiband VLA data and data from the soft x-ray satellite YOHKOH operated by the Japanese will be used to refine the model of the outer solar atmosphere.

Another probe of the outer solar corona is observations of the scattering of background cosmic radio sources. Of particular interest here is the opportunity to exploit such observations to simultaneously explore coronal turbulence on small scales through diffractive effects as well as turbulence on the largest scales, a few thousand kilometers, through refractive effects.

Solar active regions will be investigated by means of stereoscopic studies. Stereoscopic imaging takes advantage of the fact that the aspect angle toward a given feature on the sun varies owing to the sun's rotation. The method was first employed using a set of six full disk maps of the sun made with the VLA at a wavelength of 20 cm. These observations served to constrain source heights, center-to-limb variations, and source brightness temperatures. In the next year expanded efforts will see stereoscopic analysis of active regions in five VLA frequency bands.

Planetary observations in 1995 are planned to follow the changes to Jupiter wrought by the impact of comet Shoemaker-Levy 9. Shortly after the impact the 1.4 GHz flux density of Jupiter was seen to rise dramatically, with the net increase being larger than 25 percent of the pre-impact value. The magnitude and rapidity of the flux variation is unprecedented in any planetary object. Speculations include ideas that the dust associated with the comet has altered the planet's magnetosphere, and if this or similar ideas are correct the elevated flux density should persist for months or years. Observations are planned at regular intervals over the next year to monitor Jupiter's flux density.

The ongoing series of bistatic radar observations of the planets will continue in 1995. In these observations a radar signal broadcast by the NASA Goldstone antenna is reflected from a body in the solar system and received at the VLA. An image can then be constructed of the object. In 1995 major work will be done on Mercury. Previous radar observations gave evidence for high reflectivity at the poles of Mercury that was interpreted as polar ice caps. Given Mercury's proximity to the sun, the ice must be shielded from direct view of the sun and a model was developed that the water ice could, and did, survive in the shadows of deep polar craters. The idea will be given a detailed test with the radar observations this year when Mercury is at a distance of only 0.55 AU from the earth.

Radar observations are also planned of Mars and of the Galilean satellites. Observations of Mars in 1988 showed the highly reflective cap indicative of water ice from the south polar cap. Similar observations in 1992 and 1993 of the northern pole showed no such icy region. There are many possible explanations for the two results which will be explored observationally by the new work in 1995. For the Galilean satellites the observations will be exploratory work, little is known.

Passive observations of the thermal emission from the planets are also planned using the new 7 mm receiving system on the VLA. The primary targets are the Galilean satellites, although observations will also be made of Titan and of Triton and the Pluto/Charon system. A much simpler experiment to image the surfaces of Mercury and Mars will also be conducted and will yield exceptionally good surface resolution.

Theoretically, a model is being developed to describe the received radar echoes from planetary surfaces. The model involves both surface scattering and subsurface volume scattering. It will be used to constrain the types of materials and structures making up the planetary surfaces and layers immediately below the surface.

2. Stars and Stellar Evolution

The youngest stars we know of are identifiable by their thermal infrared emission as localized warm spots in an otherwise cold molecular cloud. Such young stars are commonly associated with maser emission from OH, H_2O, or CH_3OH. In either case the emission is from thermally heated gas or dust. Throughout their "youth" and "middle age," while stars are on the main sequence, the light they emit is again the result of thermally heated gas, but not entirely so. Some stars, and some regions of nearly all stars, are sources of non-thermal radiation which is reflective of the production of relativistic particles and strong magnetic fields in the stellar atmosphere or environment. At the end of their nuclear-burning lives, stars expel the successive outer regions of their atmospheres until they reach the point that most of the stellar mass has been removed. For such evolved stars the residual stellar atmosphere cools and radiates thermal molecular line emission as well as thermal dust continuum emission. Each of these three stages of stellar evolution will be investigated at the NRAO in 1995.

Early Evolution of Young Stars

Questions amenable to study with the youngest stars involve the interaction of the stars with their immediate environment. Observations will be made with the VLA at 43 GHz of the high-mass, star-formation region in Orion in an attempt to understand the origin of the continuum emission and the spatial distribution of circumstellar material. The new 7 mm capability of the VLA should allow us to discriminate the circumstellar disk dynamically and chemically from the ambient molecular cloud.

Observations of water-vapor masers will be used to trace out the very dense gas surrounding newly formed stars. Physical models of the H_2O maser emission have difficulty accounting for the rapid variability of the maser spots. A particularly intriguing model to be investigated with VLBA observations is that the H_2O masers are the sites at which a gaseous wind expelled from a young star impacts on quasi-stationary objects near the star — objects such as planets, for example. The observations planned will attempt to monitor the spatial movement of nearby maser sources to see if there are any examples of the orbital motion one might expect of a planet.

Active and Main-Sequence Stars

Non-thermal, stellar radio emission is a common phenomenon in those binary stellar systems where the binary orbit is sufficiently small that the material from one member star can overflow the Roche lobe and impact on the other star. Although the details of the physics leading to the acceleration of relativistic particles in such a gravitational transfer of material between two stars are unknown, the phenomenon is amenable to observational investigation. Examples of research in this area to be done in 1995 by members of the NRAO scientific staff include those noted below.

When the two stars comprising the binary system are both main-sequence stars, the gravitational potential well, defined by the mass and size of the more massive member of the system, is not particularly deep and the consequent acceleration of electrons is relatively modest. Electrons are accelerated to only mildly relativistic energies. Such binaries are then sources of gyro-synchrotron radio emission and weak sources of x-ray emission. One such binary system is the cataclysmic variable AE Aqr. This binary has an orbital period of ten hours. It will be observed throughout its entire orbit, and the radio data used for a physical interpretation of the time variability of the emission. Detailed VLBA imaging will be obtained of another such binary, UX Ari; observations to be made in conjunction with the ASCA x-ray satellite. The high spatial resolution of the VLBA should allow us to describe accurately the coronal structure of the star.

When one member of the stellar binary is a massive but small and highly condensed star, a white dwarf, neutron star, or black hole, the gravitational potential well is deep and steep, an ideal environment for the acceleration of highly relativistic particles. Such binary systems are found to be weak radio sources but strong sources of synchrotron and Compton x-ray emission. These "x-ray binaries" are the best source of information about how accretion disk environments serve to accelerate relativistic particles because they can be studied at wavelengths from radio waves to gamma rays. Simultaneous multi-wavelength studies are planned in 1995 to study the long-term flaring behavior of SS 433 and Cygnus X-3. This latter x-ray binary, Cygnus X-3, has been monitored daily since 1979 with the Green Bank interferometer. The data set shows that very low levels of quiescent emission precede large radio outbursts. The data set will be used to investigate this phenomenon. Specifically, models will be tested which suggest that the radio outbursts are a result of an increased accretion of material in the binary disk that initially serves to quench the radio emission via free-free absorption and later serves to enhance the emission once the material overflows the Roche lobe.

Evolved Stars

Evolved stars on the asymptotic giant branch enrich the interstellar medium with the mass they shed from their outer atmospheres. How this mass loss is initiated and maintained is not well understood. An analysis of optical data reveals a layering structure that changes with the pulsational phase of the star. An attempt will be made this year to unify these results with those from infrared spectroscopy. Infrared light samples a deeper layer of the stellar atmosphere than does optical light, and a bridging of the kinematics of hotter and cooler temperature regimes is the next step in understanding the mass-loss process.

Still further out radially in the circumstellar envelope one can study the chemistry and kinematics of the molecular gas. Using the BIMA array, maps will be made of CO and ^{13}CO of selected carbon stars for which the optical and infrared data exists. Carbon monoxide abundance ratios will allow comparison with photospheric $C/^{13}C$ ratios. Both atmospheric and circumstellar isotopic ratios are to date available for only a handful of carbon stars, and these values do not show agreement within a factor of two or more. Mapping the isotopes will give us insight into the evolutionary history of the evolution of the stars on the asymptotic giant branch since the carbon isotope ratio in evolved stars is a reflection of nuclear processes going on in the stellar interior. The synthesis of atmospheric isotopic abundances and kinematics with the structure and composition of the much larger circumstellar envelope will provide a more unified picture of this important stage of stellar evolution.

The chemistry of circumstellar envelopes will be explored with the goal of understanding the role of refractory elements. In the past year the first sodium compound, NaCN, was detected in the envelope surrounding the star IRC+10216. This follows the recent detections of additional silicon compounds (SiN, SiH_2) and magnesium as MgNC. Calcium (CaNC), aluminum (AlC), and titanium (TiN) have not been found. From all of this material a picture is emerging to describe the chemistry of refractory elements that allows an estimate of the rate at which these elements are being dispersed in the gas phase to the interstellar medium. This is of importance in studies of the gas-grain lifecycles in the interstellar medium.

The isotopic ratio $CO/^{13}CO$ will also be pursued in the remnant circumstellar envelopes surrounding planetary nebulae. For one remarkable carbon star planetary, M1-16, the CO isotopic ratio is 3, by far the lowest value known for any star. Observations with high angular resolution will be made of both CO isotopes at BIMA this year to see if there is a radial or spatial dependence to the abundance ratio.

The simplest morphology for an expelled circumstellar envelope is, of course, a spherically symmetric outflow. However, there are several indications this is an oversimplification in many cases. In the ionized gas revealed by VLA observations of the nova V1974 Cygni 1992, one can see for the first time that the ejection is asymmetric. It has a simple elliptical form where the boundaries of the major axes and inner and outer boundaries are perpendicular to each other. This morphology provides a new paradigm for modeling the spectral line shapes, light curves, and structure of nova shells that helps to explain many long-standing discrepancies. In 1995 further multi-epoch VLA observations are planned of a sample of novae for which IR and optical line profiles exist; the entire data set will be modelled with the new understanding.

The physical "cause" of the asymmetric morphology is itself the subject of an interesting speculation that will be investigated in 1995. Noting that the bipolar morphology of many planetary nebulae may be a result of a redisposition of angular momentum from a system of planets surrounding the progenitor star, the morphology necessarily indicates the presence of extra-solar planets. Here theoretical modeling is needed, but if the hypothesis proves viable it constitutes another route for the radio study of systems of planets about normal stars.

The radio probe sensitive to material in the photosphere of a mass-losing red giant star is SiO maser emission. Red giants in this class account for most of the total stellar mass recycled to the interstellar medium. SiO masers are a critical probe of the inner circumstellar envelope where mass loss originates. Earlier studies have suggested that by carefully monitoring the spectral polarization structure over time, mass motions in the envelope can be monitored. This year, such studies will continue, broadened by multi-transition spectroscopy, with full polarimetry data acquired as well.

Spatial resolution of the SiO masers will be achieved for the first time with VLBA observations. With the VLBA, maps will be made of three vibrationally excited states of SiO; a comparison of the maps will indicate whether the states are co-spatial. This is a straightforward diagnostic of the physics of the maser pumping mechanism not possible prior to the VLBA.

Further out in the circumstellar envelope one finds water masers and OH masers. Attempts will be made to understand in detail the relation of one of these species to the others and, in so doing, to understand the point in the shell that ion-molecule chemistry becomes important. The extraordinarily high spatial resolution provided by the VLBA also means that we can follow the motion of maser spots around stars and observe directly the outflow motion. Such observations are planned in the star IRC+10420 using OH masers; these same observations will give a measure for the distance to the star.

Observations with the VLBA in all the Stokes parameters offer important insights into the underlying maser process and the physical conditions in the source regions. This includes information on the distribution of the magnetic field, the high-resolution polarization morphology, and the reliable identification of individual maser components in proper motion studies. Problems to be addressed using this technique include the origin of the polarized OH maser emission and the evolution of individual SiO maser components throughout the stellar cycle. An important goal of observations in 1995 will be to determine where in the envelope the asymmetric outflow begins.

3. Supernovae and Supernova Remnants

There has been no supernova recorded in the Milky Way for the past 400 years. All our information on the supernova phenomenon comes from the study of supernovae in other galaxies and, indirectly, from observations of the sites of very old supernovae in the Milky Way. Observations of both recent supernovae beyond the Galaxy and of the remnants of historical supernovae nearby will be made in 1995.

In the past two years there have been two bright supernovae in galaxies near the Milky Way that have been observed from the northern hemisphere. Monitor observations with the VLA have been made of both supernova 1993J in the galaxy M81 and of supernova 1994I in M51 and have followed the varying radio flux density with enough precision and with enough frequency coverage that the events can be accurately modelled. In addition, a continuing series of observations of both supernovae with the VLBA is underway. These observations offer a unique opportunity for us to study directly the dynamical evolution of such objects with important implications for supernova modelling and for the use of supernovae as primary extragalactic distance indicators. The VLBA observations have enough angular resolution such that it will be possible in the next few months to construct a fully sampled, multi-wavelength movie of an exploding star.

The time evolution of even more distant supernovae is being observed in the galaxies Mkn 297 and NGC 3690. Both of these galaxies are ultraluminous, infrared galaxies, meaning that they are undergoing a rapid burst of massive star formation. One consequence of the formation of massive stars is the eventual production of an unusually large number of supernovae as the massive stars reach the end of their stellar life cycles. It is these events that are being monitored in the ultraluminous galaxies. The specific supernova in Mkn 297, SN1982aa, was discovered by its variable radio emission with the VLA; it is the most luminous radio supernova yet known. It will be interesting to follow the evolution of this object as an indicator of an extremum of the supernova phenomenon.

The two brightest supernova remnants in the Milky Way are Cassiopeia A and Taurus A. Although both are well-studied, both nevertheless present a wealth of questions amenable to study with the high resolution of the VLA and with special-purpose, low-frequency instrumentation.

Multi-epoch VLA observations of Cas A exist for more than a decade. This data set will be used to try and understand the acceleration of the clumps and filaments of gas. If the physics of the process can be understood in Cas A, it may be possible to extend that understanding to the entrainment of gas in the lobes of bright radio galaxies.

Cas A has long served as a fundamental reference source in radio astronomy because it is exceptionally bright and its flux density is predictable — the microwave flux density decreases by about one percent a year owing to the expansion, and cooling, of the remnant. However, at low frequencies, 38 MHz, the flux density of the remnant is actually seen to increase with time. This curious result, and its physical explanation, will be investigated in detail with a special-purpose, 3-element interferometer made up of log-periodic antennas and sited near the 140 Foot Telescope in Green Bank. Flux-density information will be obtained from 30-120 MHz, with the correlation done in the spectral processor. The observations will begin this year and continue annually for several years.

The other bright northern hemisphere supernova remnant is the Crab Nebula, the remnant of the supernova of AD1054. This was a type II event in all but one important respect: the swept up shell from the supernova blast wave has never been detected at any wavelength. Using the latest wide-field imaging processing techniques, the dynamic range of VLA maps of the Crab Nebula have achieved 10,000:1. In 1995 the limits will be pushed at least a factor of three lower. Finding this shell is not only important for settling the heritage of the supernova but it also allows important constraints to be placed on the mass of the progenitor star as well as on the mass-loss history of that star prior to it becoming a supernova.

Among the many effects that supernova remnants have on the material in their vicinity is the shock compression of interstellar clouds which may hasten gravitational collapse and lead to a burst of star formation. That appears to be the case for material near the supernova remnant W28. Probing the interface region between the cloud and the remnant in the OH lines, strong OH 1720 maser emission has been found with the VLA as a signature of the interaction. These data, obtained with full polarization information, will yield insight on the temperature and density of gas in the shock and on the strength and direction of the magnetic field in the regions.

4. Pulsars

Observations of pulsars have the capability to tell us something about the statistical properties of the final stages of stellar evolution, and they can be used as probes of the interstellar medium, of general relativity, and of the physics of neutron stars. All of these things will be pursued observationally in 1995.

A complete, but fast, search for pulsars in the northern sky will be concluded at the 140 Foot Telescope. This survey has already revealed five new pulsars, and the expectation is that when the data processing is complete a dozen or so new pulsars will have been discovered. To be useful elements of the pulsar data base, it will be necessary to establish precisely their pulse periods, the spin-down rates, and the orbital periods should any be in binary orbits. These follow-up observations will occur this year.

Precise timing of the most rapidly rotating pulsars, the millisecond pulsars, will continue over a longer time base. Timing measurements are useful in characterizing the pulsars themselves and also because they provide a unique means of experimentally testing terrestrial atomic clock standards and solar system ephemerides.

Precise timing requires precise knowledge of the pulsar positions. The positions can be determined exceptionally accurately with the VLBA, and such observations are planned in 1995. Moreover, since many pulsars are "running away" from the galaxy with large proper motions, it will be important to measure the motions with the VLBA and to investigate the suggestion that previous estimates of pulsar proper motion have been systematically underestimated by factors of two or three.

Two other studies will make use of the statistical properties of pulsars. First, the intrinsic variability of pulsars will be investigated by means of a study of the scintillation spectrum. The scintillation of a pulsar is observed by measuring its dynamic spectrum: a grey-scale plot of pulsar integrated flux density in a time-frequency matrix. The "scintles" in the dynamic spectrum have characteristic bandwidths and time scales which are predicted to be correlated with the pulsars time-dependent flux density. These ideas will be tested in 1995. Second, a study of the width of the pulse profile as a function of frequency will focus on the question of why that width is inversely proportional to frequency at low frequencies but above a "break" frequency it is constant. The investigation will focus on what appears to be a related phenomenon, namely, the observation that the linear pulse polarization is constant at low frequencies but rapidly decreases above the break frequency. A model of both phenomena, including a physical explanation for the correlation, has been developed and will be used to confront the observations in 1995.

Another pulsar association to be studied is that of pulsars with supernova remnants. Although pulsars are commonly assumed to be the stellar relics of supernova explosions, there are but few spatial coincidences between the two seen on the sky. Sensitive imaging studies with the VLA will focus on this question by looking for weak, non-thermal emission in the vicinity of pulsars for which the spin-down age is less than 60,000 years. The work has the prospect of telling us about the periods, magnetic fields, and space velocities of pulsars as they are formed as well as information about the environment in which they were deposited.

Studies of individual pulsars have been proposed as a follow-on to one of the most successful programs conducted at the NRAO in 1993 and 1994, and that is confirmation of the speculation that soft gamma-ray repeaters are in fact pulsars. The soft gamma ray repeater SGR 1806-20 was suggested to be physically associated with the supernova remnant G10.0-0.3 owing mostly to a coincidence on the sky. However, in 1993 the Compton Gamma Ray Observatory detected a soft gamma ray event from SGR1806-20 at the same time that the x-ray satellite ASCA also saw a transient burst and established that the burst came from the direction of G10.0-0.3. With this information it is clear that the key to a better understanding of the energetics and origin of the soft gamma ray repeater phenomenon lies in the study of the nebulae that surround neutron stars. In 1995 the VLA will be used to search for other likely associations.

Finally, using a special-purpose, 3-element, low-frequency interferometer, an investigation will be made into the intriguing suggestion that a pulsar with a 0.4-second period can be seen at the Galactic center at 30 MHz. If the reported detection is confirmed, the observation will have an influence on models of the physics of the Galactic center region.

5. Molecular Clouds and Star Formation

Star formation is such a profoundly complicated process because it surely involves the chemistry, density, temperature, magnetic field, and kinematics of the material that will make up the star. Our knowledge of all of these parameters of a molecular cloud is still poor. Nevertheless, we can make some progress in our understanding by probing molecular clouds, and young stars, both on the large-scale, entire molecular clouds, and on the smallest scales, the protostars themselves. Observations are planned this year to map the thermal dust emission from molecular clouds, to look at the spectroscopic signature of molecular material by means of a large number of emission lines, and to look at the physics and dynamics of molecular clouds on the smallest spatial scales by means of absorption observations. The star-formation "problem" won't be solved in 1995, but surely a greater understanding will be achieved.

The chemistry of molecular clouds will be explored through a variety of studies designed to increase our understanding of what molecular constituents are present and at what concentration. Secondarily, of course, we would like to know why those constituents are present, that is, we would like to know the chemical process by which they came into being. One now extensive study has surveyed all CO isotopes, formaldehyde, ammonia, HCO^+, and N_2H^+, as well as CS, C_3H_2, HCN, and HC_3N. All these species can be modelled with a cloud in hydrostatic equilibrium, a polytrope, which allows a complete specification of the physical conditions needed to understand the excitation, hence the abundances and chemistry of the various molecular species. These have been chosen to answer specific questions about the chemistry, and seem to be indicating grain chemistry for some species and ion molecule chemistry for others. In 1995 observations of HNC will be added to the existing HCN observations and allow certain key nitrogen processes to be isolated. Various sulfur species (SO, HCS^+, SO_2) will complement CS in an attempt to answer long-standing mysteries about interstellar sulfur chemistry which is now very poorly understood. Preliminary SiO observations will be followed up to confirm the present indication that it can be formed by ion molecule processes in small clouds and does not require shocks or strong heating of grains as often assumed.

On the smallest spatial scale, absorption observations of molecular clouds will be made of those clouds that are in the foreground of bright, small, extragalactic radio sources. These observations allow us to probe in detail the chemistry and kinematics of galactic molecular clouds. In 1995 a chemical survey of about a dozen molecular species, all seen in absorption, will be completed in five clouds seen in the direction of background continuum sources. These data will be compared with the emission line data in an attempt to compare the small-scale cloud chemistry with the global cloud chemistry. Over a period of months to years the absorption line observations will be repeated; any variability in the line profile can be attributed to micro-arcsecond variations in the abundance or kinematics of the foreground molecular cloud.

Absorption observations with the VLA of OH will complement the millimeter-wave absorption observations. Here the suggestion that HCO^+ is commonly seen in absorption in clouds even when CO emission is weak implies that the HCO^+ has its origin in diffuse clouds where H^2 and HI are about equally abundant. If this is correct, OH is the predecessor of HCO^+ in much the same way that HCO^+ is the antecedent of CO. The VLA OH absorption observations will provide a critical test of this idea.

Turning our attention now from the cloud as a whole to the regions forming low mass stars, we find that the molecules which emit strongly are those whose abundance has been enhanced by low temperature chemistry, DCO^+, HDO, and NH_2D. Such regions are highly localized and are known as "cold cores." The coldest cores have been shown to be fruitful locales in which to seek the youngest stars. Various such regions have been studied by means of ammonia observations with the VLA. In these maps differences between the objects become very apparent. In objects so young that no bipolar flow has yet begun, ammonia structures are readily detectable. In another group of cold cores, very cold ammonia exists, but it shows little spatial correlation with cold dust condensations which should mark the location of the protostar. In a final group of objects, warm ammonia correlates well with the dust emission and shows up in the outflowing gas as well. It appears as if ammonia becomes severely depleted, perhaps as a result of freezing onto dust grains, in the final stages before the cold core becomes a self-luminous protostar. In 1995 these ideas will be investigated by means of the new 7 mm system on the VLA. Here the hope is to see the thermal dust continuum emission and compare its spatial extent with the ammonia maps, a comparison which should answer many questions about the earliest stages of star formation.

Once the cold cores become self-luminous protostars, they can be studied by a variety of techniques at radio, millimeter-wave, and infrared wavelengths. An important suggestion is that young, low-mass stars are thought to be preferentially in binary systems. But it is entirely unknown whether these systems form during the protostellar or pre-main sequence evolution. To determine the binary fraction of embedded young stars a program of high angular resolution, 3 and 5 micron imaging will be undertaken.

Newly luminous protostars exhibit a marked kinematic signature as well as the thermal signature of a localized warming of the molecular cloud that will be studied with the infrared observations. The initial stellar luminosity disperses from the vicinity of the protostar cloud material near the star. The outflowing material often has a "bipolar" or hourglass structure, with gas flowing away from the star in opposite directions along a common axis. In order to estimate the mechanical energy in the outflow one needs to know whether the observed matter is primary stellar wind material or is it material swept up from the ambient molecular cloud. Observations designed to answer this question are planned of the protostar SVS-13. The plan is to complete a multi-transition study of HCO^+ to determine the excitation of the outflow: if the gas is highly excited it is likely part of the stellar wind; if not, it is ambient cloud material. In either case it is already known that the outflow has structure on angular scales less than 20", and for this reason the single-dish HCO^+ observations will be complemented with observations from the OVRO and BIMA arrays.

The physics of bipolar outflow protostars is itself the subject of theoretical modeling with focus on the question of how the molecular material may be accelerated to high velocities. The velocities observed in outflows indicate that the driving wind must originate deep within the potential well of the star. The temperatures and densities expected within a few stellar radii in a disk or wind are well-matched to the excitation conditions for the first overtone rotation-vibration bands of CO at 2.3 microns. However, in a sample of objects chosen to have evidence of a protostellar or accretion disk, only 20 percent show the CO 2.3 micron bands in emission. In the next year models of the disk and wind will be extended to examine why some stars show CO emission and others do not. This will help to reveal whether the CO is tracing the excitation conditions in the disk or in wind material.

6. Emission Nebulae

Ionized gas excited by bright stars is both a conspicuous component of spiral galaxies such as the Milky Way, and it is a physical environment well-suited to a comparison of our understanding of physics with our understanding of astronomy. Several such tests will be undertaken in 1995.

With the sensitivity of the current generation of radio telescopes, we have two spectroscopic probes of the ionized gas excited by O and early B-type stars. In these HII regions one can measure both the strength of the recombination lines, H^+ and He^+, and the kinematics they describe, but also the fine-structure line of the once ionized isotope of helium, $^3He^+$. From the standpoint of trying to understand the physics of HII regions, having both these lines is critically important because the intensity of the recombination lines is proportional to the square of the density of electrons in the nebula, whereas the intensity of the helium-3 fine-structure line is linearly proportional to the electron density. With both lines we get a reliable measure of the density clumping in ionized nebulae, and with this we can interpret accurately the excitation and abundance of both hydrogen and helium. For several bright galactic HII regions, the recombination-line strength and the strength of the helium fine structure line are known from single-dish observations. The brightness of the H^+

recombination line has been mapped with the VLA for many of the same regions. In 1995 the $^3He^+$ line will be mapped with the VLA and a comparison of all the data, single-dish and VLA, H^+ and $^3He^+$, will be used to construct a unified model of radio HII regions.

The heating and cooling of ionized astrophysical environments will also be put to a novel test. A few evolved red giant stars are found in binary orbits with early B stars which have a significant hydrogen ionizing flux. The bright star Antares is such a system. The B star companion orbits within the circumstellar shell of the mass-losing red giant, and as it does so it ionizes the gas in its immediate vicinity. The region of ionization orbits the red giant just as the B star does. Material "upstream" in the orbit is progressively ionized and material "downstream" in the orbit recombines and cools. A multi-epoch VLA study of this phenomenon will be conducted to image the process and to compare the observational details with our understanding of the physics of photoionization, recombination, and collisional cooling.

The youngest O stars, still embedded in the molecular cloud from which they formed, give rise to highly compact HII regions. They are compact both because they are newly ionized and because the ionization front proceeds only slowly in the dense environment of the molecular cloud. Recombination-line observations of several such "ultracompact" HII regions will be made with the VLA in an attempt to measure the kinematics of the expansion of the HII region and to refer that result to models of the evolution of young nebulae.

Spatially adjacent to expanding and evolving HII regions are regions of the molecular cloud that are in the process of being ionized but have not yet become so. These "photodissociation" regions will be studied with VLA observations of the C^+ recombination line in an attempt to understand just how dense, hot, and clumpy the partially ionized gas may be.

Further away from the HII region in the molecular cloud the gas will still be neutral, having not yet been exposed to the ionizing stellar radiation, but it is subjected to compression owing to the leading shock wave preceding the stellar ionization front. In this compressed gas we observe maser emission from abundant constituents of the molecular cloud, in particular from OH and H_2O. High-resolution, multi-epoch VLA and VLBA observations will be made of several HII region/molecular cloud complexes in order to elucidate the origin and kinematics of the regions of molecular maser emission.

7. The Galaxy

Gas in the interstellar medium continually changes its phase in response to local conditions. Gas closely exposed to starlight is ionized or heated, cold tenuous gas will be neutral but largely atomic, cold dense gas will combine into a molecular form or find itself deposited into dust grains. Understanding the quantity of gas in each form and understanding the large-scale processes which cause changes between them are the subject of several studies by NRAO staff in 1995.

Using as probes of the interstellar medium HI, CO, and IRAS (dust) observations together with deep optical imaging, an attempt will be made to compare the various tracers of the cold interstellar medium on arcminute-size scales over regions several degrees in extent. The goals include a determination of the mass of gas in HI filaments compared to the HI in broader structures and then, later, a comparison of the same fractions for the molecular gas.

Mosaic images of the HI in the Milky Way will be made with the VLA over large (degrees) regions at high Galactic latitude. Care will be taken to create the images with good velocity resolution, less than 2 km/s, so that the gaseous filaments can be well separated from the more diffuse gas.

The interstellar hydrogen emission line at 21 cm wavelength will also be used for studies of the Zeeman effect at the 140 Foot Telescope. The observations will provide a measure of the magnitude and direction of the interstellar magnetic field, the disposition of which is a major unknown in interstellar studies — the magnetic field could control the dynamics of some regions and yet be a minor constituent of the interstellar energy balance in other regions. Measurement of the Zeeman effect is quite demanding and long integrations as well as careful consideration of possible systematic effects are necessary. There are only a handful of detections that are currently accepted as reliable; the addition of even a few more would greatly enhance our understanding of the interstellar magnetic field.

Further away from the disk of the Milky Way hydrogen clouds seem to be falling into the Galaxy at high velocity. These high-velocity clouds (HVCs) are mysterious both in origin, distance from us, and composition. A survey for HVCs toward QSOs is in progress. The HI data will be combined with UV observations from the Hubble Space Telescope in the hope that it will be possible to learn of the abundances in the clouds. With that information we can infer something of the origin and history of the HVC gas. For example, higher than usual abundances of refractory elements would indicate shock disruption of grains that might be expected if HVCs were ejected from the disk of the Galaxy. An abnormally low metallicity HVC would be one from an early phase of star formation in the Galaxy.

At the center of the Milky Way the gas motions and distribution is very different from that seen locally. Motions in excess of 250 km/s are commonly seen as material orbits close to the galactic center and plumes of gas are found perpendicular to the plane of the galaxy. The energetics of all these phenomena are hard to explain and the relation of one to another is utterly unknown. In an attempt to unravel some of the mystery, a large mosaic image, three degrees on a side, will be made of the galactic center region with the VLA. The image will be used to search for the origin of the non-thermal filaments and continuum braids of emission seen near Sgr A and Sgr C.

Finally, the dust component of the interstellar medium will be studied using the "IRAS Atlas of Dark Clouds" now being assembled collaboratively at the NRAO. Algorithms have been developed that calculate the dust temperature and optical depth and, using these, the images of the dust in dark clouds have been constructed. The atlas will have many uses because it will be a complete, all-sky, high spatial-resolution catalog of all dark clouds more than 5 degrees from the Galactic plane. The atlas will be made available for release on a CD-ROM.

8. Normal Galaxies and Clusters

Elliptical Galaxies

Elliptical galaxies are dominated by older stars and show little evidence for gas and dust. Nevertheless, we see indirect evidence for the presence of a rich interstellar medium in some ellipticals either because we see evidence for star formation or we see non-thermal radio jets emerging from the galactic nuclei, evidence that matter is being deposited on a central black hole. Understanding elliptical galaxies depends to some extent on understanding the origin, distribution, and fate of the interstellar gas.

More than 20 elliptical galaxies show detectable HI 21 cm emission. A comparison of VLA HI images of this sample of galaxies will be used to gain an overview of the amount, distribution, and kinematics of cold gas in stellar systems very different from the spiral galaxies commonly studied in HI emission. Further, by selecting galaxies with reasonably extended HI for detailed study, it will be possible to use the HI observations to learn of the dynamics of the underlying galaxian gravitational potential both with regard to its shape and total mass involved.

The elliptical galaxy M84 hosts a FR-I radio continuum source. Its two jets visible on VLA maps are asymmetric near the galactic nucleus, but at greater distance from the nucleus they become increasingly symmetric. VLBA observations in 1995 will be made of the nuclear region to see if in fact the parsec-scale nuclear jets (a) exist, and (b) if they do, do they show the same asymmetry as the large-scale jets. If they do then this result would imply a common physical process for the symmetrization process operable on both the parsec and kiloparsec scale. One such process is Doppler boosting in a relativistic flow. Owing to the proximity of M84, it will be possible both with the VLA and the VLBA to observe relativistic proper motion if indeed it is present, so this particular idea can be directly tested.

Spiral Galaxies

Dusty, gas-rich, spiral galaxies are active sites of star formation, their interstellar medium is loosely bound to the gravitational potential of the gaseous disk, and the gaseous material responds to the gravitational tidal forces as one galaxy passes by another. Study of the interstellar disk gas therefore provides a diagnostic of the gravitational dynamical history of a galaxy. There are a number of important questions that can be addressed with radio observations.

The spatial distribution of the interstellar gas within galaxies supplies a vital link in our understanding of global star formation within these systems. Thus, in Sa-type galaxies the HI appears to be exterior to spiral arms and the molecular gas, CO, is centrally concentrated. What fuels the star formation, evidenced by the presence of HII regions, within the spiral arms? In many later-type spirals a significant fraction of the most common constituent of the interstellar medium, HI, lies exterior to the optical galaxy. Is this a reservoir for future star formation? If so, how is it driven interior to the optical disk of the galaxy? Is the presence of faint companion galaxies necessary for continued star formation? How does material from evolved stars in the bulge region of spiral galaxies interact with the cooler interstellar medium located exterior to the bulge? These are some of the questions to be addressed with observations in the radio continuum, in the HI 21 cm line, and with molecular line observations.

VLA HI observations of the nearby spiral galaxy M81 have been made over a sufficiently large area to include several dwarf galaxies that are companions to M81. The dynamical role the dwarf companions play on the organization of the interstellar medium in M81 is being modeled. The HI in M81 itself is not at all uniform; rather it can be described as knotty with dense clumps interspersed among regions of deficient HI emission. Attempts will be made to understand the gas structure and the interaction of the gas clumps in the arms and interarm regions with regions of currently active star formation. Carbon monoxide observations made with the BIMA array of M81 and NGC 628 will be made to determine the role gravitational waves play in the star-formation process in disk galaxies.

Observations of HI made with the VLA provide not only detailed images of where the gaseous interstellar medium is found within spiral galaxies, but additionally they provide unparalleled kinematic resolution, < 1 km/s. The exceptional velocity resolution will be exploited in HI observations of two face-on galaxies, NGC 1058 and DDO 196, to measure how the gas kinetic temperature changes with radius and whether the velocity dispersion varies on small scales (e.g., near regions of star formation). These measurements are important both for understanding the gas-heating mechanism and in dynamical attempts to use the thickness of the gas layer to constrain the shape of dark matter halos.

Ring galaxies provide a particularly rich case for studies of star formation in the wake of gravitational shocks. Thermal radiation is expected from new star-forming regions just behind the shock wave. Non-thermal radiation from supernovae would be expected to lag further behind in the wake of the shock wave. VLA data have been obtained of 13 ring galaxies, and a comparison is underway to investigate the detail in which the observations are in agreement with the theoretical ideas.

The nearby spiral galaxies are desirable to study because our angular resolution corresponds to finer spatial details in the nearby galaxies than in the more distant objects. Unfortunately, the angular size of the nearby spirals is also larger than the main beam of the VLA antennas. The only way one can image these galaxies is to construct a mosaic image. Algorithms to handle these cases are in place now and observations are planned in 1995 of the spiral galaxy nearest the Milky Way, IC 342.

The problem with bright nearby spirals being larger in angular size than the VLA primary antenna beam of nearly 35 arc minutes is exacerbated many times over for molecular-line observations made with the 12 Meter Telescope where the antenna beam at CO(J=1-0) is less than one arc minute. In order to measure accurately the molecular content of the galaxies, techniques have been developed for the astronomer to scan rapidly over the entire galactic disk. The "on-the-fly" techniques open doors for observations of the molecular content of nearby galaxies that will be exploited in 1995.

The rate of current star formation in Sa galaxies is low. These objects are dominated by a central bulge of older stars, surrounded by a feeble disk. However, the rate of current star formation is not zero. In many Sa galaxies there are scattered knots in the outer disk which could be HII regions surrounding hot young stars. These knots are difficult to explain in terms of the distribution of cool material as it is now understood, since it is generally believed that the atomic hydrogen often lies outside the optical disk and the molecular hydrogen lies within the bulge. New CO observations will be made of three Sa galaxies for which earlier observations suggest that the CO distribution is extended. The additional observations will be used to determine if the CO is in a ring and, moreover, if the ring coincides with the region of weak star formation. The answers will guide further discussion of such questions as whether the rate of star formation is consistent with the amount of material found; whether other early galaxies with star formation in the outer regions might also have extended emission in CO; and why the early galaxies in which the CO is centrally concentrated do not show evidence of recent star formation in the central bulge.

New synthesis observations of CO in the starburst galaxy He2-10 show in detail the distribution of gas in the star-forming regions. The observations indicate that there are two or more distinct systems of molecular gas which may be colliding or merging and causing enhanced star formation. Analysis of the gas motions allows an estimate of the total mass and suggests that unusually young star clusters comprise half the total mass near the galaxy's center. In the coming year the HI distribution measured with the VLA will be used with the CO data to study the efficiency with which gas has been consumed in the star-formation process. Analysis will be made of the data obtained with the VLA for the similar galaxy NGC 3125 to examine the possibility that it too contains massive star clusters, and CO/HI observations of the active galaxy Tololo 1924-416 will be started.

A new radio probe of nearby active galaxies, radio-recombination-line observations, will begin of the southern galaxies NGC 4945 and the Circinus galaxy. These observations have the potential to allow us to see in detail the starburst phenomenon that is hidden from view at visual wavelengths. They will reveal the nature and amount of ionized gas in the nuclear regions and also the kinematics of the gas within the central hundred parsecs.

Irregular and Dwarf Galaxies

Low-mass, gas-rich galaxies that lack a clear morphological structure are referred to collectively as irregular galaxies. Among the properties they share are these: the star-formation rate is low even though the ratio of gas mass to stellar mass is as high as, or higher than, that in active spiral galaxies; the metallicity is low. Understanding the history and evolution of irregular galaxies is a high priority for a detailed understanding of those spiral galaxies that are gravitationally influenced by irregular or dwarf galaxies.

Optical spectra of some irregular galaxies are dominated by emission lines and appear very blue. These HII galaxies, like I Zwicky 18 or GR 8, have extremely low, heavy-element abundances. Based on a new optical survey with the Russian 6 meter telescope, about a dozen more objects with similarly low abundances have been found. VLA and HST observations in 1995 will be used to explore about five of these systems further in the expectation that we can learn of the cause of the low metal abundances.

In a recent VLA survey of 20 HII galaxies it was found that 70 percent have at least one and sometimes several HI companion clouds. This implies that the hypothesis that interactions of HI clouds is the trigger that "ignites" star formation in HII galaxies is indeed valid. Deep optical imaging has failed to uncover any optical counterparts. The HI clouds appear therefore to be gas clouds with few, if any, luminous stars.

A new technique has been developed, and will be explored in 1995 to probe the heavy element abundance in the neutral interstellar medium in dwarf galaxies. In I Zwicky 18 HST was used to obtain OI absorption spectra toward a bright OB star cluster. As the HST spectral resolution is inadequate to resolve the line, the assumption was made that the OI line width was identical to the HI line width. The VLA gives a good measure of the HI spectral line, and combining the VLA and HST data leads to an abundance ratio of OI in I Zwicky 18 that is 1/1000th that in the solar system. The technique will be applied to other dwarf galaxies in 1995 to see how widespread the phenomenon may be.

Radio continuum measurements have been made of the non-active counterparts to HII galaxies, the low surface brightness (LSB) dwarf galaxies. These observations will be compared with the IRAS far-IR observations to see if the radio continuum *vs* far-IR correlation breaks down at low radio luminosity. If it does, then we have an argument that the correlation is related more to the confinement of energetic particles in the disk of a galaxy than it is to the production mechanism for those particles.

Searches for young, embedded star clusters in dark clouds in the Magellanic clouds will be carried out using the near-IR camera at CTIO. Such clusters are well observed in Galactic molecular clouds, but little work had been done on identifying their counterparts in the Magellanic cloud galaxies. The observations are designed to investigate the distribution of star formation within individual clouds as a function of position within the LMC itself. It should also be possible to constrain the cluster luminosity function for the LMC.

HII regions excited by a single identifiable star will also be observed in the large Magellanic cloud. The main goal of the observations is to establish an observational evolutionary sequence for such HII regions by correlating the observed physical properties (emission-line luminosities, electron temperatures, densities, radio-continuum morphologies) with the spectral type and luminosity class of the ionizing star.

Finally, the first systematic survey for the 6.6 GHz line of methanol will be made of all the IRAS-selected ultracompact HII regions in the Magellanic clouds. The purpose of the survey is to examine the effects of low metallicity on the existence of methanol masers, an effect previously seen for OH and H_2O masers, and to identify a sample of masers for subsequent VLBI studies. With regard to the latter, the detected methanol masers will be phased-referenced with background VLBI continuum sources seen in the same fields as the methanol masers so that the transverse motion of the LMC and SMC can be established. The transverse, proper motion, together with the kinematic radial motion will define precisely the orbit of the Magellanic clouds. The orbit in turn will define for us the mass of the local group, and having that we will know the mass-to-light ratio of the local group and the fraction of that mass that is dark matter.

Galaxy Formation, Interactions, Physics, and Dynamics

The physics of the mechanism by which galaxies produce radio emission will be explored with a complete sample of VLA images of all 347 UGC galaxies in the declination range between +5 and +75 degrees that are stronger than 25 mJy at 6 cm wavelength. The images of all 347 galaxies will be used to distinguish, by radio morphology alone, the "starbursts," whose radio energy source is star formation, from the "Monsters," whose radio energy source is accretion onto a supermassive black hole. Independent luminosity functions will be constructed for starburst and monsters, plus steep- and flat-spectrum sources in order to model the cosmological evolution of sources at 6 cm. For the monster UGC galaxies, radio core positions and jet orientations will be used to clarify the tendency toward minor-axis ejection and to investigate the phenomenon of "sloshing" of the galactic nuclei. The monster UGC galaxies, which emit at low power levels, will be targeted for (1) future VLBA searches for relativistic jets which may hold the key for unification theories; (2) VLA HI absorption searches for atomic gas falling toward the supermassive black holes; and (3) HST searches for stellar cusps, gas and dust disks, optical jets, and luminous blue star clusters.

The correlation between the mass of molecular hydrogen in a galaxy and the rate of star formation is well established, but there is considerable scatter in the relationship. There are galaxies that have the same, large mass of H_2 but have star-formation rates that differ by a factor of 100 or so. For the same molecular content, more active galaxies tend to show disturbed morphology, molecular gas concentrated near the nucleus, and proportionally more high-density gas. To understand galaxy structure and to have insight on galaxy formation and evolution, it is essential to understand the distribution and characteristics of molecular gas in galaxies. To this end the $z = 2.3$ luminous galaxy IRAS F10214+4724 will be observed with interferometric CO observations to investigate the relationship between chemical and structural evolution. Observations of a $z < 0.1$ galaxy, Arp 220, will be used as a comparison object for the more distant galaxy observations.

Analysis of QSO absorption-line systems find evidence of strong evolution in the population of absorbing clouds. Those with the highest column densities are the damped lyman-alpha absorbers commonly believed to be the disks of young spiral galaxies. Searches in 1995 will be made for CO emission in these objects as an attempt to determine the global gas mass, and optical searches will be made for [OIII] emission from the young stars bound in the system.

VLA HI observations will be made of the luminous interacting galaxy Arp 105 which may serve as a nearby prototype of the more luminous and much younger galaxies, such as F10214+4724 and Arp 220. The Arp 105 system is an elliptical galaxy in the process of merging with a spiral galaxy. Huge gas tails stretch 100 kpc to either side of the spiral. All of the HI in the system is found in these tidal tails, with major concentrations near the ends. No HI is detected in the merging objects. The HI clumps near the ends of the tails contain newly formed stars. These objects could become self-gravitating and detach from the tails, making them dwarf galaxies in their own right rather than tidal debris. Strong CO is found exclusively at the center of the merging activity. Analysis and modeling of this system will be completed in 1995.

Ocular galaxies are interacting systems which are caught at a very particular time in their interaction, when one of the objects displays a strong double arm which gives it the appearance of an eye. One of the better examples is the galaxy IC 2163 which is interacting with NGC 2207. Because the ocular structure is short-lived and because it calls for a prograde tidal interaction in the plane of the disk, the number of possible orbits one has to explore in modeling the system is small. VLA HI observations and numerical modeling will be conducted in 1995 for the IC 2163/NGC 2207 system.

Physical explanations for the non-axisymmetric structures in galaxy velocity fields will be sought by study of the HI equatorial ring around the elliptical galaxy IC 2006. Earlier work has shown that harmonic analysis of the residuals to a circular fit to the rotation can place limits on the symmetry of the gravitational potential. The new investigation will concentrate on applying $m = 1$ and $m = 2$ distortions to an isolated ring to see in what detail observations of gas tracers can be used to constrain the detailed shape of a galaxy's gravitational potential field.

Galaxy Clusters

Galaxies in the cores of clusters of galaxies differ from those in the field in their morphological type, stellar population, and gaseous content. Optical observations suggest that the cluster environment does speed up the evolution of galaxies. Thus by studying galaxies in clusters even over a moderate range of redshifts of 0 to 0.4, it will be possible to observe galaxies being transformed from normal galaxies to starburst to gas-poor to old galaxies. Neutral hydrogen observations of galaxies in clusters have heretofore been limited to velocities less than 10,000 km/s. It is instructive to compare a distant cluster with a nearby one from many points of view: the HI mass to blue luminosity relation and the HI deficiency of cluster galaxies are but two examples. With this in mind, a program will begin to study the evolution between z = 0 and z = 0.4. The cluster to be studied is one for which detailed photometry and spectroscopy is available. In 1995 the VLA HI observations will be added to this data base.

The Butcher-Oemler effect is the occurrence of a higher proportion of blue galaxies in clusters as the redshift increases to 0.5 (at least). It is believed that these blue galaxies in high redshift clusters probably contain large amounts of gas and may be undergoing enhanced star formation. A completely independent way of testing this is to look for enhanced radio emission from the blue galaxies. This will resolve some of the difficulties with interpreting the Butcher-Oemler effect as an evolutionary effect. With this in mind, four clusters will be observed with the VLA: two are at a redshift of 0.25 but have blue galaxy population fractions of 0.19 and 0.03; the other two clusters are at a redshift of 0.38 and have blue galaxy fractions of 0.21 and 0.16, respectively. The number of detected radio sources with optical counterparts can be expected to be very different in these clusters. A detailed study of the galaxies will be made in regard to their colors, morphology, and spectral signature with the goal of understanding their evolution.

9. Radio Galaxies, Active Galaxies, and QSOs

The luminous radio sources associated with active galaxies and quasi-stellar objects are among the most energetic objects in the universe. Since they represent such an extremum, an understanding of the physics involved in such objects presents us with an opportunity to discover the limits to which our understanding of physics can be properly applied. To this end we seek the properties common among the energetic radio sources and, once that can be established, we seek to understand the underlying physical mechanisms. In addition, because the energetic radio sources are found over a range of cosmological epoch they can be used as probes of the cosmological evolution of the environment surrounding, within, or along the line of sight to energetic galaxies. Research in both these general areas will be conducted at the NRAO in 1995.

Source Physics

Recent attempts to describe the radiation mechanism for virtually all radio galaxies, galaxies with active nuclei and QSOs, within the framework of a common model have met with some success. The model, the "unification scheme" model, has as its cornerstone a super-massive blackhole surrounded by a disk of gaseous matter, the accretion disk, the material from which is continually flowing to the black hole. The gravitational energy released in the process drives the radio jets we observe. The precise details of the observations depend critically on our viewing angle both because the radio jets appear to travel at relativistic speeds and because the accretion disk is optically thick at visual and near-IR wavelengths. Observations of a large number of sources are needed to test the validity of the model and, where appropriate, make modifications to it.

The role of relativistic bulk motions in determining apparent side-to-side asymmetries in double radio sources will be studied in three ways.

First, the VLA will be used to study the spectral index and depolarization asymmetries of the lobes in a sample of powerful double-lobed radio galaxies with detected radio jets. A previous study of such asymmetries in a sample of 3CR quasars with one-sided radio jets has shown that the features with high surface brightness have flatter radio spectra in the lobe facing the jet, whereas the features with low surface brightness have systematically flatter spectra in the longer lobe. Both of these effects have important consequences for radio source models that attribute such asymmetries to relativistic effects. The high-brightness correlation mimics the depolarization asymmetry seen in radio-loud quasars. It shows that whatever causes the jet-sidedness asymmetry in such quasars extends beyond the jets into the brighter parts of the lobes. In conventional models the vector for this asymmetry is bulk relativistic flow, and the extension of such flow into the lobes is surprising unless at least part of the flow in the jets has higher Lorentz factors than had previously been suspected. The low-brightness correlation mimics the length-related depolarization asymmetry seen in powerful radio galaxies. It shows that some lobe asymmetries are independent of jet sidedness and may reflect asymmetries in the gaseous environments of the sources. It is important to determine whether these two correlations are replicated in a sample of powerful double-lobed 3CR radio galaxies as well as in the quasar sample. The extent to which they appear in both radio galaxies and quasars is a new test for relativistic jet models and for proposed unifications of these radio-loud source populations.

Second, the fine structure of the total and polarized intensity of the jet and counterjet in the low-power radio galaxy 3C 31 will be determined from sensitive, high-resolution VLA observations at several frequencies. Several lines of evidence now point toward a model of radio jets in which an inner, ultra-relativistic, highly-collimated spine surrounds itself with a boundary layer or sheath in which flow velocities decrease outwards from the spine. In this model, many asymmetries in both plumed and double-lobed sources may be attributed to differences in the longitudinal deceleration of the spine and of the sheath, and by orientation-sensitive aspects of both parts of the flow. 3C 31 is a particularly good laboratory in which to test such spine-sheath models. The model predicts strong relationships between the intensity asymmetries, apparent magnetic field configurations, polarized intensity, and depolarization distributions across 3C 31. These will be tested in detail.

Third, the VLBA will be used to seek evidence that even a low-power radio galaxy can contain a jet with a relativistically-moving spine. The compact features at the base of the jet in the weak, twin-plumed radio source in the Virgo cluster elliptical M84 will be imaged at several epochs to determine, or set limits to, their apparent proper motions.

Superluminal motions are a common feature of many galaxies with active nuclei and of the quasars. 3C 120 is one such object for which superluminal motion has been established on scales of 50-100 parsecs. VLA observations of the kiloparsec radio structure indicated that the relativistic motion could be seen even on these large scales, a result that has an important bearing on the source energetics. The result was not confirmed by observations with MERLIN. An attempt will be made this year to reconcile the conflicting results.

The dominance of superluminal motion on the parsec scale of AGNs and QSOs implies specific predictions for the spectral evolution of radiating material in the radio jet. These ideas will be tested for the first time using the VLBA capability for nearly simultaneous observations at many frequencies.

Observation of superluminal motion can only occur if the radio jet is beamed very closely along our line of sight. When this is not the case we expect to see either no jet at all or we will observe a comparatively slow, non-relativistic jet. In either case we expect to see the extended and presumably nearly stationary radio lobes. As a test of this simple idea the first phase of a VLBI survey of the motions in the cores of a sample of lobe-dominated QSOs has been made. Unexpectedly, superluminal motion does occur frequently in this class of source albeit only from studying a small number of objects. VLBA observations of the complete sample of objects are planned to see if the preliminary result obtains in a statistically significant sample.

Two observations suggest that the region of particle acceleration in QSOs is extraordinarily small; confirming observations will be sought in 1995. First, VLBA observations of the nearest radio galaxy, Centaurus A, indicate that the compact radio source in this object is smaller than 0.0002 arcseconds, or given the distance to the galaxy, this is a size corresponding to less than five light-days. Second, another VLBA program will be directed to unraveling the origin of the intra-day variability seen in some compact extragalactic objects. Taken at face value the intra-day variability suggests a source size less than a few light-hours. The VLBA observations will be used to search for structural variability on the same time scales.

Finally, observations of the cores of both core-dominated and lobe-dominated radio sources at 90 GHz reveal that the cores of lobe dominated sources are statistically more inverted than the core dominated sources. This runs counter to the model in which the core dominated sources are relativistically beamed if their spectrum turns over in the submillimeter. An investigation will be conducted this year to determine if the phenomenon extends to different morphological classes of radio sources and to see if there is a trend of core spectral index with core dominance.

Source Environment

The strength, morphology, and polarization characteristics of distant extended radio sources depends on the environment in which the radio sources are embedded. In this sense, study of the radio sources is inexorably a study of the magneto-ionic environment also. Since the environment evolves with cosmic epoch one can, in principle, study that evolution by studying radio sources over a range in redshift.

Multi-frequency, multi-configuration VLA observations with full polarization are planned to observe the extended radio source 3C 31 to try and understand the process of source deceleration and entrainment of the ambient gas which appears to be important to the source physics in 3C 31. Similar observations are also planned of 3C 449 where variations of spectral index throughout the jets and lobes are indicators of regions of particle acceleration.

High-fidelity VLBI observations of the QSO 3C 48 showed that it is likely that the radio jet was disrupted on scales of less than an arcsecond. This suggests a strong interaction with the interstellar medium and provides a clue to the nature of compact, steep spectrum sources as well as to the density and mass of an interstellar cloud at redshifts of 0.1.

The ambient density of magneto-ionic material in the vicinity of the QSO 3C 119 will be investigated by VLBA observations. 3C 119 is a compact, steep-spectrum radio source with structure on milli-arcsecond scales. It has a high rotation measure and it depolarizes at short wavelengths. Rotation measure maps should clarify whether these characteristics are due to an unusually high concentration of thermal electrons in the source environment or whether it is due to gas surrounding the source. If observations support the latter hypothesis, this will also lend weight to the hypothesis that the complex structures seen in many compact, steep spectrum radio sources result from interaction with their environments.

Similar polarimetry observations will be made of the compact, steep spectrum quasar 3C 138. Multi-frequency polarimetry will be applied to the task of determining whether this object contains the dense plasma believed responsible for the appearance of this class of objects and the observations as well will provide a view of the magnetic field structure.

A combination of radio, VLA, and x-ray, ROSAT, observations will be used to explore in detail the temperature, density, and extent of hot gas within clusters of galaxies as follows:

- In 1995 a x-ray/radio study of radio galaxies will be extended to nearby radio galaxies to test the idea that all FR I radio galaxies lie in rich cluster-like environments.
- A sample of distant, very rich, Abell clusters will be used in a study of the evolution of the radio source population. The same data-set can be used in a search for background sources which are gravitationally lensed by the cluster.
- Detailed observations of the clusters Abell 400 and 2634 will be used to test ideas about cluster merging and of the bending of radio sources that are attached to the central cluster galaxies.

10. Radio Surveys and Cosmology

One of the first applications for radio astronomical observations was to cosmology. The simplest idea was tested with the first 100 or so radio sources identified: increasingly distant sources should be fainter than nearby sources but there should be more distant than nearby sources. These early tests spawned generation after generation of increasingly sophisticated tests that continue to this day. However, now surveys are used as tests not only of cosmology but of the evolution of radio sources, of the spectroscopic character and polarization properties of evolving galaxies, and even of the chemistry of molecular clouds nearby and far. In addition, surveys are needed to establish the "standards" for radio astronomy from which instruments are calibrated and diverse observations referred. Much survey work will go on at the NRAO in 1995.

The 1.4 GHz NRAO VLA Sky Survey should cover the sky north of declination -40 degrees by the end of 1996. The principal data products will be a set of 2326 continuum map cubes 4 degrees on a side containing Stokes I, Q, and U images; and tables of the positions and intensities of discrete radio sources. All this information will be stored and accessible to users on the Internet.

Two sets of maps covering the declination range from 0 to +75 degrees have been made from the epoch 1986 and epoch 1987 Green Bank 4.85 GHz surveys made with the 300 Foot Telescope. Differences between these maps will be used to study the variability of sources in flux-limited samples and to find transient sources. Data from both epochs have been combined to produce a set of maps with lower noise and source position uncertainties. A catalog of sources stronger than 19 mJy will be prepared from the maps. Maps covering the southern declination zones have been constructed from observations made with the Parkes Telescope in Australia. A CD-ROM containing all the maps and the source catalogs covering the whole sky will be produced in 1995. This CD-ROM will also include software permitting PC users to display and analyze the FITS-format maps.

Exceptionally deep VLA images offer an opportunity to study the nature of very faint radio sources. Observations made in 1994 at 8.4 GHz reached a limiting flux density of 9 microjansky for individual sources in a small field previously observed at optical wavelengths and with the HST. A statistical study of the VLA image gives information on the source density down to 2 microjansky, orders of magnitude weaker than is possible with any other instrument. At these levels of sensitivity there is close correspondence between radio and optical emission, unlike for bright galaxies and strong radio sources where there is little association. Based on optical morphology and spectra, together with their measured angular size and radio spectral distribution, it has been tentatively concluded that the population of microjansky radio sources is linked to disk galaxies with enhanced star formation, likely induced by galaxy interactions or mergers. At microjansky levels there are relatively few quasars and classical radio galaxies as these are apparently all included in surveys at the millijansky level. Further VLA observations are planned with improved sensitivity and resolution needed to resolve blends of sources as well as for comparison with the "repaired" HST images.

In a separate investigation, previously unidentified radio sources from the Parkes catalogue are being used to search for very high redshift quasars. Since most flat spectrum radio sources are associated with quasars, it seems likely that those that remain unidentified on ordinary images taken at visual wavelengths may have such large redshifts ($z > 5$) that the Lyman cutoff is shifted into the visible. Optical/IR spectroscopic observations are planned of all the previously unidentified radio flat-spectrum sources, using the VLA positions as a guide.

Observations with the VLA at 1.4 GHz will be made of a complete sample of 244 far-IR sources seen coincident with the positions of x-ray sources. The sample represents the largest homogeneous sample of FIR-selected galaxies yet detected in x-rays. The objectives are to study the correlation between the radio and x-ray luminosities of galaxies and to compare the radio properties of x-ray sources powered by both mechanisms. Both the x-ray (ROSAT) and IR (IRAS) data have relatively poor spatial resolutions. Therefore, the VLA observations are essential to establish the positional identification.

Radio sources powered by star-forming galaxies obey the remarkably tight far-infrared to radio luminosity correlation. Consequently, flux-limited samples of such galaxies selected in the radio and far-IR bands are nearly identical. The combination of the IRAS FSC2 data and data from the new NVSS will be used to search for high redshift, ultra-luminous galaxies such as F10214+4724.

A survey of very compact radio sources is underway as a joint collaboration between the NRAO and Jodrell Bank. The survey will make VLBA observations of 3000 candidate phase-reference sources, by far the largest number of sources ever surveyed with VLBI techniques. The primary aims are to assemble an all-sky catalog of VLBA calibrators with 1 or 2 milli-arcsecond astrometric positions. Structural information for each source will be available at 2.2 and 8.4 GHz. Proper motion studies and radio-optical reference frame alignment are then enabled; the latter is particularly important in the Hipparchos and HST era. In addition to the utility of the catalog for VLBA calibration, the same work will provide scientific returns in the form of a sample of small-separation gravitational lens candidates and the statistics of lensing by masses of a million solar masses or more. With repeated observations, it will be possible to use the sources for cosmological studies.

At millimeter wavelengths the number of bright sources, and their positions, is even more poorly known. Current catalogs of millimeter sources are incomplete at flux density levels less than 1 Jy and there are few sources known within ten degrees of the galactic plane.

In 1995 attempts will be made with the VLA 43 GHz system to increase the number of known millimeter-wave calibrators. The work this year should yield at least 1000 such calibration sources. A similar survey is planned in the southern hemisphere with the Australia Telescope and with SEST.

All the above survey work is either directed to assembling large samples of objects selected by certain criteria or it is meant to improve our knowledge of the statistical properties of a previously defined class of object. Other surveys planned in 1995 adopt a different approach and are highly directed to answer specific questions. Examples include those mentioned below.

Measurement of the fluctuations of the microwave sky brightness will be made on angular scales of a degree. Gravitational perturbations in the early universe are the seeds for the formation of the large-scale structures we see in the universe today. These fluctuations leave a lasting imprint on the cosmic microwave background in the form of temperature anisotropies. Once the magnitude of the fluctuations of primordial origin are determined, power spectrum estimation as a function of angular scale will allow a distinction to be made between competing cosmological theories. Observations to this end will be made from Saskatoon, Saskatchewan during January and February with a new Q-band detector system developed in part at the CDL.

Another observational task of long-standing and great importance is the identification of the source of the gamma ray bursters. After nearly 20 years of study we still don't know if the bursts have their origin near the solar system or at the edge of the universe. Our knowledge of the energy involved is also terribly incomplete. In an attempt to see if radio bursts accompany the gamma ray bursts, a large effort will be made to scan the 140 Foot Telescope over the fields of reported gamma ray bursts; if the radio bursts are found, good positions can be established and an identification can be made.

Searches will continue for galaxies in formation early in the history of the universe by means of both searches for HI emission and CO emission. The VLA at 330 MHz will be used to search for redshifted HI emission in protoclusters of galaxies. The VLA sensitivity allows masses of hydrogen in excess of several times 10^{12} solar masses to be identified. Better limits can be obtained at millimeter waves from searches for redshifted CO emission at the 12 Meter Telescope. Here, limits of less than 10^{11} solar masses of molecular hydrogen can be found, and targets in 1995 will include distant radio galaxies, quasars, and the damped lyman alpha absorption systems.

Finally, line searches in our local environment are an important part of unraveling the chemistry of the interstellar gas. In 1995 a spectral survey of the 2 mm atmospheric window, 135 - 170 GHz in selected objects, will be concluded. These observations include the first comprehensive comparative study of the chemistry of several star-forming regions of various evolutionary phases and that of the circumstellar envelope surrounding the IR star IRC+10216. A comparison of these two regions will be particularly illuminating because it is a comparison of the chemistry of matter in interstellar clouds with the chemistry of the source of the enriched material, the circumstellar environment.

11. Instrumentation and Observing Techniques

Through experimentation with new instrumentation and new observing techniques, the NRAO staff scientists are better able to assist the observing programs of visiting scientists and they become more knowledgeable about potential areas of improvement for the facilities. Much of this work is done in partnership with the scheduled observing programs of the visiting scientists but some, noted below, has its own independent direction that will, if successful, contribute to the research resources at the NRAO available for visitors.

Mapping neutral atomic hydrogen in the 21 cm line places a heavy demand on the single-dish telescopes. The areas to be covered when mapping galactic hydrogen are often enormous, many tens of square degrees. One way to facilitate mapping is to construct an array of feeds and a suitable combining network so that multiple beams can be generated simultaneously. A prototype array is being designed and fabricated for this purpose as a proof of concept. The algorithms for combining the beams, and even correcting for telescope imperfections, are also in the planning and debugging stage.

At millimeter wavelengths, where the primary telescope beams are an arcminute or less, an on-the-fly technique is being developed in Tucson that will greatly speed up mapping programs. The technique, which can be used for either spectral-line or continuum mapping, involves keeping track in real-time of where the telescope was pointing as it is driven across the source. After the fact, the data are regridded onto a regular grid and mapped. Optimization algorithms for the data taking and data analysis will be developed in 1995.

Polarization mapping with a single-dish antenna and with VLBI observations have been problems of long standing; both will be addressed with new instrumentation and observing techniques in 1995. At millimeter wavelengths a rotating polarimeter has been installed in the optical path at the 12 Meter Telescope and will be used for linear polarization measurements of interstellar spectral lines. The observing techniques, and calibration techniques, needed to optimize the use of the polarimeter will be investigated with the cooperation of visiting observers at the 12 Meter Telescope. In the case of VLBI observations, the availability of the VLBA has meant that full polarization data can be obtained. However, as with the case with the millimeter-wave polarization data, the difficulty is in calibrating the polarization, basically extracting the instrumental polarization from the polarization of the astronomical source. Here a novel technique is being explored that involves using astronomical maser emission as a polarization calibrator for continuum sources. Observational tests of the idea are planned with the VLBA in 1995.

Continuing in 1995 and extending for several years will be work done on problems involved in reconstructing images from VLBI arrays, including arrays with one radio antenna in earth orbit. In such arrays all of the long baselines usually involve a single antenna, the orbiter, and there is a wide gap in (u,v)-plane coverage between baselines involving other antennas. It has been recognized for some time that these characteristics lead to difficulties in deconvolution due to the missing spacings and in applying self-calibration techniques to the data, but there has been little research on dealing with these problems. Basically, the essence of the problem is that it is difficult to disentangle instrumental changes at the orbiting antenna from source structure visible only on the longest baselines. Strategies for dealing with this type of data will be required to make the best use of observations with the VSOP and Radioastron satellite antennas due to be launched in 1996 and 1997, respectively.

Finally, substantial work will go on in 1995 on the software problem in astronomy. Astronomers are often faced with difficulty in bridging the gap between isolated software programs for piecemeal data reduction and software designed for theoretical modeling of physical phenomena. Attempts will be made to reconcile the two via assembly of an object-oriented library of tasks extracted from both environments in order to make it easier for scientists to program for the entirety of their work rather than for selected aspects of it.

APPENDIX B - SCIENTIFIC STAFF

(Does not include Visiting Appointments)

D. S. Adler - Interstellar medium in the Milky Way and external galaxies; molecular clouds; observations and computational studies of the dynamics of spiral galaxies; star clusters; star formation

D. S. Balser - Physics of HII regions and planetary nebulae; abundances in the interstellar medium

C. S. Barnbaum - Evolved stars: kinematics, isotopic abundances, circumstellar structure

T. S. Bastian - Solar/stellar radio physics; solar/stellar activity; wave propagation in random media; radiative processes; particle acceleration; interferometry

A. J. Beasley - Radio interferometry; VLBI observing techniques

J. M. Benson - Extragalactic radio sources; VLBI image processing

R. C. Bignell - Polarization and imaging of extragalactic radio sources; planetary nebulae; supernovae remnants

A. H. Bridle - Extragalactic radio sources

E. Brinks - Interstellar medium in nearby galaxies; HI studies of galaxies; star-forming dwarf galaxies

R. L. Brown - Theoretical astrophysics; interstellar medium; quasar absorption lines

W. R. Burns - Information theory and signal processing

B. Butler - Radar astronomy; planets and planetary surfaces; the solar system

C. J. Chandler - Millimeter/submillimeter observations of molecular clouds and star formation; near-infrared spectroscopy of young stars

B. G. Clark - VLBA control; software development

M. J. Claussen - Interstellar masers; circumstellar masers; interferometry; young stellar objects; compact and ultracompact HII regions; centimeter and millimeter-wave molecular spectroscopy; spectropolarimetry; radio recombination lines

J. J. Condon - QSOs; normal galaxies; extragalactic radio sources

J. E. Conway - Extragalactic radio sources; jets in radio sources; VLBI observing techniques; extragalactic radio supernova and supernova remnants

T. J. Cornwell - Interferometry; image reconstruction methods; coherence theory; radio source scintillation

W. D. Cotton - Extragalactic radio sources; interferometry; computational techniques for data analysis

L. R. D'Addario - Theory of synthesis telescopes; superconducting electronics; millimeter wavelength receivers; radio astronomy from space

V. Dhawan - Extragalactic radio sources; VLBI; instrumentation

P. J. Diamond - Spectral line interferometry; VLBI; software development

K. S. Dwarakanath - Clusters of galaxies; interstellar medium; aperture synthesis at low frequencies

D. T. Emerson - Nearby galaxies; star formation regions; millimeter wave instrumentation

J. R. Fisher - Cosmology; signal processing; antenna design

C. Flatters - VLBI polarization studies of extragalactic radio sources

E. B. Fomalont - Interferometry; extragalactic radio sources; relativity tests

D. A. Frail - Interstellar medium; pulsars; supernova and nova remnants; radio stars

G. A. Fuller - Star formation; galactic molecular clouds

R. W. Garwood - Galactic 21-cm line absorption; interstellar medium; high redshift 21 cm line absorption

F. D. Ghigo - Interacting galaxies; extragalactic radio sources; interferometry

B. Glendenning - Starburst galaxies; scientific visualization

M. A. Gordon - CO; galactic structure; gas-rich galaxies; interstellar medium

W. M. Goss - Galactic line studies; pulsars; nearby galaxies

E. W. Greisen - Structure of the interstellar medium; computer analysis of astronomical data

J. L. Higdon - Multi-wavelength studies of star formation in interacting galaxies; primeval galaxies; galaxy kinematics

R. M. Hjellming - Radio stars; radio and x-ray observations of x-ray binaries; interstellar medium

D. E. Hogg - Radio stars and stellar winds; early-type galaxies

M. A. Holdaway - Image reconstruction methods; VLBI polarimetry

P. R. Jewell - Circumstellar shells; interstellar molecules; cometary line emission

K. I. Kellermann - Radio galaxies; quasars; VLBI

A. R. Kerr - Millimeter-wave development

L. J. King - Antenna structural/mechanical analysis and design; optimization methods for antenna structural performance

L. Kogan - Maser radio sources; theory of interferometry; software for data reduction of VLBI

G. I. Langston - Gravitational lenses; computational techniques for synthesis imaging

W. B. Latter - Astrochemistry; interstellar medium; mass loss processes; planetary nebulae; magnetic white dwarfs

H. S. Liszt - Molecular lines; galactic structure

F. J. Lockman - Galactic structure; interstellar medium; HII regions

R. J. Maddalena - The structure, kinematics, evolution, distribution, and physical properties of molecular clouds; how nearby star formation alters clouds; the relationship of atomic and ionized gases to molecular material

M. M. McKinnon - Plasma astrophysics; pulsars; stellar radio emission; signal processing

P. J. Napier - Antenna and instrumentation systems for radio astronomy

J. Navarro - Pulsars; interstellar medium; image processing techniques

D. J. Nice - Pulsars; interstellar medium; interstellar scintillation

F. N. Owen - Clusters of galaxies; QSOs; radio stars

J. M. Payne - Telescope optics; millimeter-wave receivers; cryogenic systems

R. A. Perley - Radio galaxies; QSOs; interferometer techniques

M. Pospieszalski - Low noise front-ends and amplifiers; theory and measurement of noise in electronic devices and circuits

S.J.E. Radford - Starburst galaxies, millimeter interferometry

M. S. Roberts - Properties and kinematics of galaxies

J. D. Romney - Active extragalactic radio sources; VLBI; interferometer imaging

A. Roy - Active galaxies; Seyfert, starburst, luminous infrared galaxies, radio galaxies; extragalactic radio recombination lines; indirect imaging techniques

M. P. Rupen - Interstellar medium of early type galaxies; galaxy dynamics through radio/millimeter observations; radio supernovae; steep spectrum radio sources

R. A. Simon - Theory of interferometry; computational imaging; VLBI

R. A. Sramek - Normal galaxies; quasars; astrometry; supernovae

A. R. Thompson - Interferometry; frequency coordination and atmospheric effects; distant extragalactic sources

B. E. Turner - Galactic and extragalactic interstellar molecules; interstellar chemistry; galactic structure

J. M. Uson - Clusters of galaxies; cosmology

P. A. Vanden Bout - Interstellar medium; molecular clouds; star formation

G. A. Van Moorsel - Dynamics of galaxies and groups of galaxies; methods and techniques for astronomical image analysis

R. C. Walker - Interferometric observations of extragalactic radio sources; VLBI calibration and imaging methods; high dynamic range interferometer imaging.

D. C. Wells - Digital image processing; extragalactic research

E. M. Wilcots - HII regions in the Magellanic clouds; HI and the interstellar medium in nearby galaxies; extragalactic star formation; structure and evolution of barred Magellanic irregular galaxies

E. Wollack - Cosmology: cosmic microwave background—spectrum, anisotropy, and polarization—observations; radio source counts: fluctuations; instrumentation and techniques for radio astronomy

D. S. Wood - Star formation; HII regions and the interstellar medium; radio and infrared astronomy; interferometry and infrared arrays; atomic and molecular spectroscopy

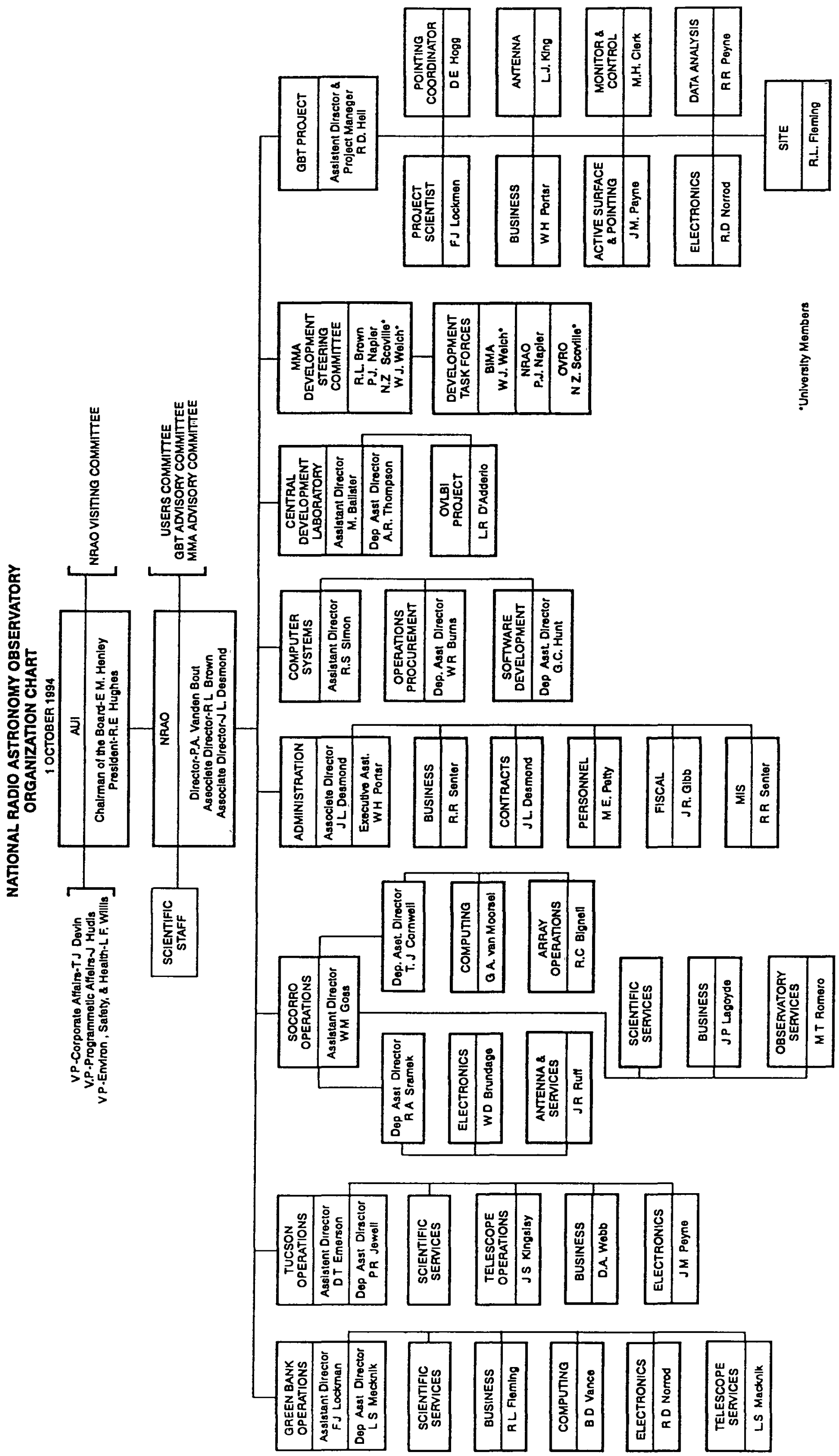
A. H. Wootten - Star formation; structure, spectroscopy and chemistry of the interstellar medium in galaxies; circumstellar material

J. M. Wrobel - Normal galaxies; active galaxies; polarimetry

Q.-F. Yin - Normal galaxies; imaging techniques

A. Zensus - VLBI observations of quasars and active galactic nuclei; compact radio jets and superluminal motion in compact radio sources

APPENDIX C - ORGANIZATION CHART



APPENDIX D - NRAO COMMITTEES

1. AUI Visiting Committee

The Visiting Committee is appointed by the AUI Board of Trustees and formally reports to the AUI Board on an annual basis. Its function is to review the performance of the Observatory and to advise the Trustees on how well it is carrying out its function as a national center, the quality of the scientific work, and the adequacy of its instrumentation and facilities.

Current membership is:

E. C. Churchwell	University of Wisconsin - Madison
N. J. Evans	University of Texas
J. N. Hewitt	Massachusetts Institute of Technology
K. Y. Lo	University of Illinois
A. P. Marscher	Boston University
J. Pipher	University of Rochester
A. I. Sargent	California Institute of Technology

Two additional members to be appointed.

2. NRAO Users Committee

The Users Committee is made up of users and potential users of NRAO facilities from throughout the scientific community. It advises the Director and the Observatory staff on all aspects of Observatory activities that affect the users of the telescopes (development of radiometers and auxiliary instrumentation; operation of the telescopes; the computer and other support facilities; and major new instruments). This committee, which is appointed by the Director, meets annually in May or June.

Current membership is:

M. A. Barsony	Center for Astrophysics
M. Bell	Herzberg Institute of Astrophysics
E. B. Churchwell	University of Wisconsin
J. M. Cordes	Cornell University
J. M. Dickey	University of Minnesota
D. M. Elmegreen	Vassar College Observatory

R. S. Foster	Naval Research Laboratory
A. S. Fruchter	University of California, Berkeley
R. A. Gaume	Naval Research Laboratory
C. R. Gwinn	University of California, Santa Barbara
D. H. Hough	Trinity University
C. J. Lonsdale	Haystack Observatory
K. M. Menten	Center for Astrophysics
L. G. Mundy	University of Maryland
R. Mutel	University of Iowa
M. J. Reid	Center for Astrophysics
R. Taylor	University of Calgary
J. Turner	University of California, Los Angeles
S. C. Unwin	California Institute of Technology
J. Van Gorkom	Columbia University
R. A. Windhorst	Arizona State University
D. Woody	California Institute of Technology

3. Green Bank Telescope Advisory Committee

Appointed at the inception of the Green Bank Telescope (GBT) project in 1989, this committee reviews periodically the design planning for the GBT. Initially the committee advised the Director on critical design issues facing the GBT project: staffing, decisions, and decision-making process of the GBT design team. The committee may identify alternative design techniques or suggest specific tasks. Construction review and proposed instrumentation are future areas of concern to the Committee.

The committee is appointed by the Director. It is composed of scientists and engineers representing the range of skills—structural, mechanical, electrical, computational, and scientific—needed for the telescope design and construction.

Current membership is:

M. P. Haynes	Cornell University
C. Heiles	University of California, Berkeley
R. A. Jennings	University of Virginia
J. D. Nelson	University of California, Berkeley
V. Radhakrishnan	Raman Research Institute

S. von Hoerner	Independent Telescope Consultant
S. Weinreb	Martin Marietta Laboratories
R. W. Wilson	Bell Laboratories

4. Millimeter Array Advisory Committee

The NRAO Director is aided in the planning process for the Millimeter Array (MMA) by the MMA Advisory Committee. Members of the Committee are experienced in the design of millimeter instruments and facilities. At the annual meeting held in the fall of the year, the Committee is asked to review and comment on the technical direction of the MMA project. With the advent of the MMA Development Consortium (MDC), the Advisory Committee membership is being revised to include solely those from institutions not part of the MDC.

Current membership is:

J. H. Bieging	University of Arizona
N. Erickson	University of Massachusetts
N. J. Evans	University of Texas
R. Hills	Cavendish Laboratory, UK
G. R. Knapp	Princeton University
C. R. Masson	Center for Astrophysics
R. W. Wilson	Bell Laboratories
C. G. Wynn-Williams	University of Hawaii

(Additional membership pending.)