THE MILLIMETER ARRAY

Project Overview and Status

August 1995

The Millimeter Array is a facility proposed to the National Science Foundation by Associated Universities, Inc., on behalf of the National Radio Astronomy Observatory.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated by Associated Universities, Inc.

THE MILLIMETER ARRAY: A WINDOW ON BEGINNINGS

What did the universe look like 12 billion years ago? How do galaxies form? How do stars form? Where do planets, complex molecules and the beginnings of life come from? The answer to all these questions involves cosmic clouds of cold gas. The origin of everything we know in the universe is locked up in accumulations of cold matter. The key to that lock is the Millimeter Array.

What is the Millimeter Array? The Millimeter Array (MMA) is a radio telescope. It is designed to operate at wavelengths of 0.8 - 9 millimeters where the Earth's atmosphere is partially transparent and where clouds of cold gas as close as the nearest stars as well as clouds as distant as the observable bounds of the universe all have their characteristic spectral signatures. It will observe gas clouds near the sun in which stars can be seen forming now and it will observe galaxies in their formative stages at the edge of the universe which we see as they were 10 billion years ago. The MMA provides a window on celestial origins that encompasses fully and uniquely both space and time.

The Millimeter Array is a synthesis telescope. It consists of 40 precision antennas each 8 meters in diameter all operating in concert to simulate a single antenna as large as 3000 meters in diameter. The signals from the individual antennas are processed in a special purpose computer or signal correlator. Images of astronomical objects are made using algorithms to correct for atmospheric propagation effects and for the fact that the "synthesized" telescope is in fact made up of a number of individual antennas. In a very real sense the image-forming "optics" of the MMA is a computer.

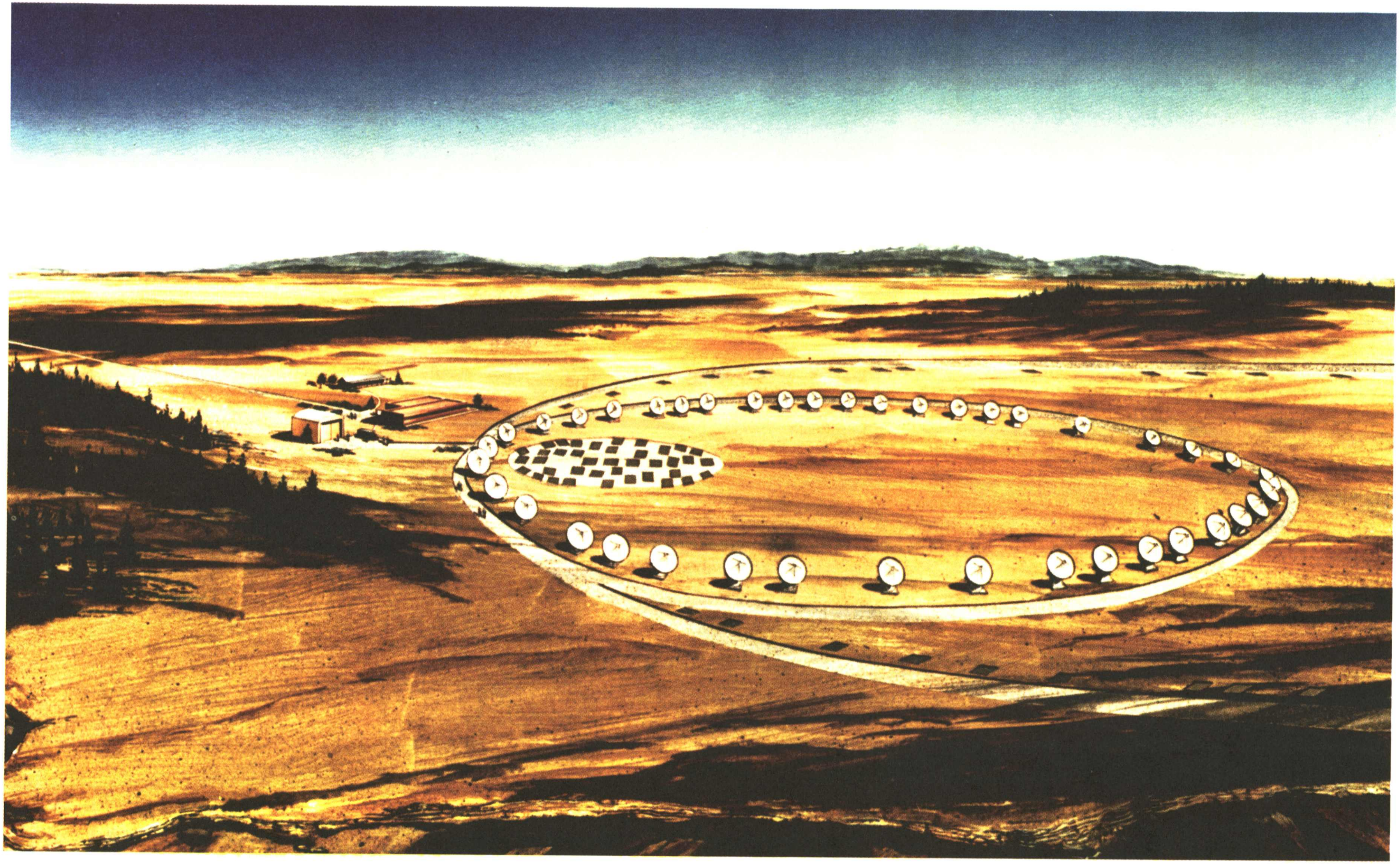
By employing these proven imaging techniques, the MMA will provide images superior in quality and detail to those obtained with the Hubble Space Telescope and it will do so at a wavelength where objects in the process of formation are visible. The MMA is revolutionary in its concept, design and scale: there is no instrument yet like the MMA.

To operate efficiently, indeed, to operate at all at the highest frequencies for which it is designed, the MMA must be located on a high, dry, flat site. The NRAO is currently studying a site at 5000 meters (16,500 feet) elevation in the eastern Atacama Desert of northern Chile. Initial data looks very promising for this site, where conditions appear to rival even those at the South Pole for lack of water vapor. Mauna Kea, on the big island of Hawaii, is an alternative site.

The Millimeter Array is a proposal to the National Science Foundation made by Associated Universities Inc., on behalf of the National Radio Astronomy Observatory (NRAO). The NRAO is federally owned, one of the national astronomy centers of the National Science Foundation. The NRAO is operated by a private not-for-profit research management contractor, Associated Universities, Inc. The NRAO exists to build and operate radio telescopes for the benefit of the U.S. scientific community that are of such a scale and size that they are beyond the resources of a single state or university. Observing time on NRAO telescopes is made available on the basis of scientific merit alone. Annually, nearly 800 astronomers, including about 150 students, from 180 different institutions use NRAO telescopes.

The MMA is expected to cost close to $200M. A project of this magnitude, and an instrument with the scientific impact of the MMA, is properly an international enterprise; the National Science Foundation is accordingly seeking to make the MMA a reality in partnership with other interested countries. The schedule for the project anticipates the detailed scientific and technical design phase extending to the year 1999, which will also be the first of six years of construction. Interim scientific operations should be possible with the partially complete array early in the century, with full operation by 2005.

Once constructed the MMA will be the radio telescope equivalent to the optical Keck telescope, the largest in the world. It will also be more than the equivalent of the Hubble Space Telescope in terms of the detail of its astronomical images, and it will provide the generations of scientists and students that use it with a unique opportunity to study the cosmos in its nascency.



Artists concept of the Millimeter Array. The forty 8-meter antennas may be rearranged in any of 4 ellipsoidal configurations that are 70, 250, 1000 and 3000m in extent respectively.

THE SCIENTIFIC IMPACT OF THE MILLIMETER ARRAY

The Millimeter Array combines the sensitivity provided by the collecting area of a telescope fifty meters in diameter with sub-arcsecond angular resolution superior to that of the Hubble Space Telescope, and it operates at frequencies at which thermal processes illuminate the sky. The forty 8 meter antenna elements comprising the array give the synthesized telescope a rapid snapshot imaging capability so precise that wide-field mosaic imaging will be a uniquely important MMA capability. This unprecedented combination of sensitivity, angular resolution, and imaging fidelity at short wavelengths will make available for astronomical investigation a wealth of unique opportunities and new science. Scientists using the MMA will:

- Image the redshifted dust continuum 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;
- Assess the influence that chemical and isotopic gradients in galactic disks have on star formation and spiral structure;
- Image heavily obscured regions containing protostars, and protostellar and preplanetary disks in nearby molecular clouds, with a spatial resolution of 10 AU and kinematic resolution < 1 km s^{-1}.
- Detect the photospheric emission from hundreds of nearby stars in every part of the Hertzsprung-Russell (H-R) diagram.
- Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of stellar nuclear processing and envelope convection;
- Resolve the dust formation region and probe the structure of the magnetic field in stellar winds;
- Establish the relative distributions of the large number of complex molecular species in regions of star formation, relating them to shock fronts, grain disruption, and energetic outflows – information which is essential to the understanding of astrochemistry;
- Obtain unobscured sub-arsecond images of cometary nuclei, hundreds of asteroids, planetary atmospheres and surfaces, and solar regions of active particle acceleration.

GROUND BREAKING RESEARCH WITH THE MMA: EXAMPLES

An instrument such as the MMA that provides a significant increase in both image detail and sensitivity over existing instruments can be expected to provide its users with opportunities to do new science. It should not simply permit the *old* science to be done faster. The MMA provides many such opportunities for ground breaking research; three examples are the following.

1. **The Formation of Galaxies**

   The MMA will image the gas and dust in mass accumulations that are in the process of becoming galaxies. The gas spectroscopic observations will reveal the mass and kinematics of the forming galaxies at a time preceding the formation of stars when the protogalaxy is still *dark*. The MMA will be capable of imaging many thousands of such galaxies, only the few brightest of which can be observed today. One example is the ultraluminous galaxy F10214+4724 shown on the following page. The F10214+4724 image was made with the Owens Valley Radio Observatory interferometer. The contours are of the CO(3-2) emission seen at a redshift of 2.286, and the color image is an optical image made with the Keck telescope.

2. **The Formation of Protostars and Protoplanets**

   Images of star-forming regions from the MMA will be made at long enough wavelengths that the cloud of gas and dust that obscures our view of newly forming stars becomes transparent. The MMA images will have enough detail to allow astronomers to see chemical variations in protoplanetary systems and to permit them to compare such systems with evolutionary models of our own solar system.

3. **Images of Stellar Nucleosynthesis**

   In the final stage in the life of all stars somewhat more massive than the sun, the star will blow off most of its matter in a gigantic wind. The outermost parts of that wind were at one time the outer layers of the star; the inner parts were formerly the innermost core of the star. Detailed observations with the MMA will allow astronomers to *read* the history of stellar nucleosynthesis by observing chemical and isotopic gradients from inside to outside in these winds. The great resolution and sensitivity of the MMA are indispensible for this research to be extended to the thousands of other such stars distributed throughout the Milky Way. An example of such studies, observations of CS, CN, SiS, and SiC_2 made with the IRAM interferometer of the nearest and brightest evolved star, IRC+10216, are shown below.

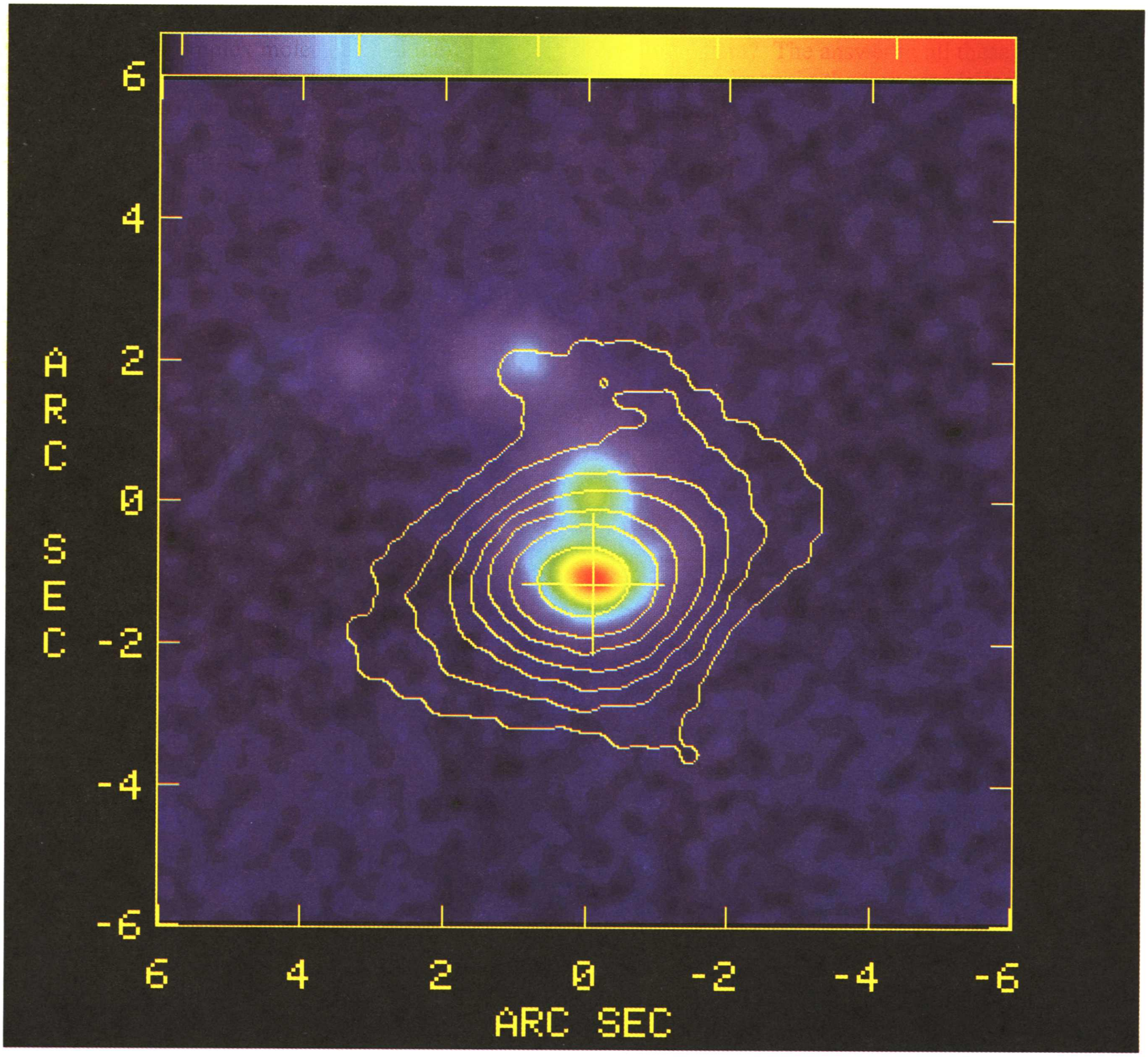
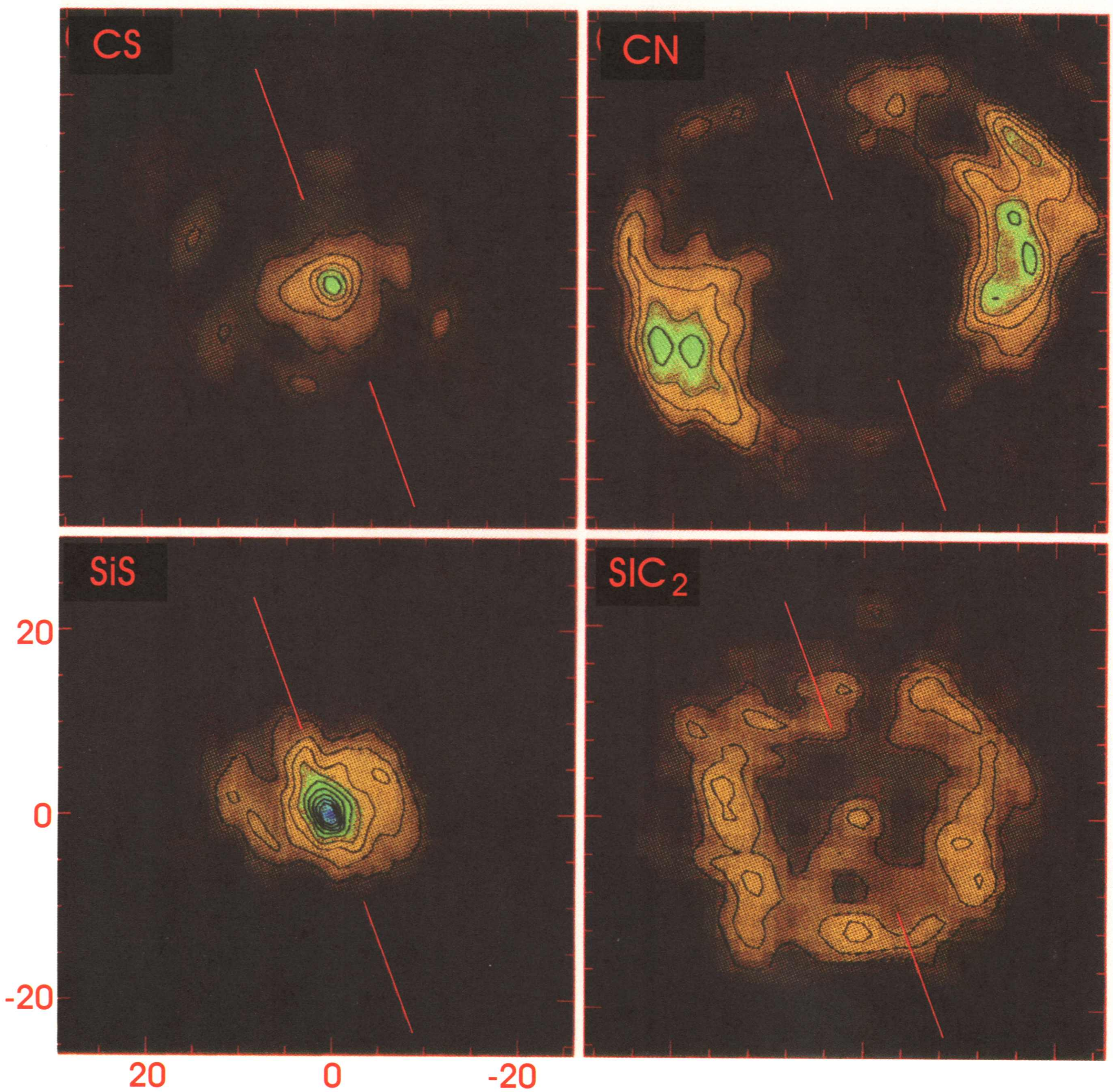


Image of the carbon monoxide emission from a galaxy 12 billion light-years distant from the earth. The CO emission from the z=2.286 galaxy F10214+4724 made by the Owens Valley Radio Observatory array (contours) is shown superposed on an optical photograph from the Keck Observatory,



Images of the stellar atmosphere expelled from the aging star IRC+10216.
The CS, CN, SiS and SiC_2 images were made by the IRAM interferometer.

MILLIMETER ARRAY: TECHNICAL DESCRIPTION

The Millimeter Array is made up of forty precision antennas that are transportable among four array layouts or configurations. The transportability and reconfigurability gives the MMA a *zoom-lens* capability. In its most compact configuration the MMA achieves a wide field of view used for imaging large objects such as galaxies, molecular clouds or the disk of the sun; in its most expanded configuration the MMA realizes its highest angular resolution for imaging with the greatest detail.

Antennas

The forty 8-meter antennas will be used 24 hours a day, and they will be fully exposed to the environment (sun and wind). There is no enclosure. The antennas will maintain a parabolic figure accurate to less than 20 micrometers, and they will point accurately to a precision of one second of arc. To overcome thermal distortion, the antennas may be constructed partially of composite material. The current engineering design of an antenna that meets these specifications is shown on the next page.

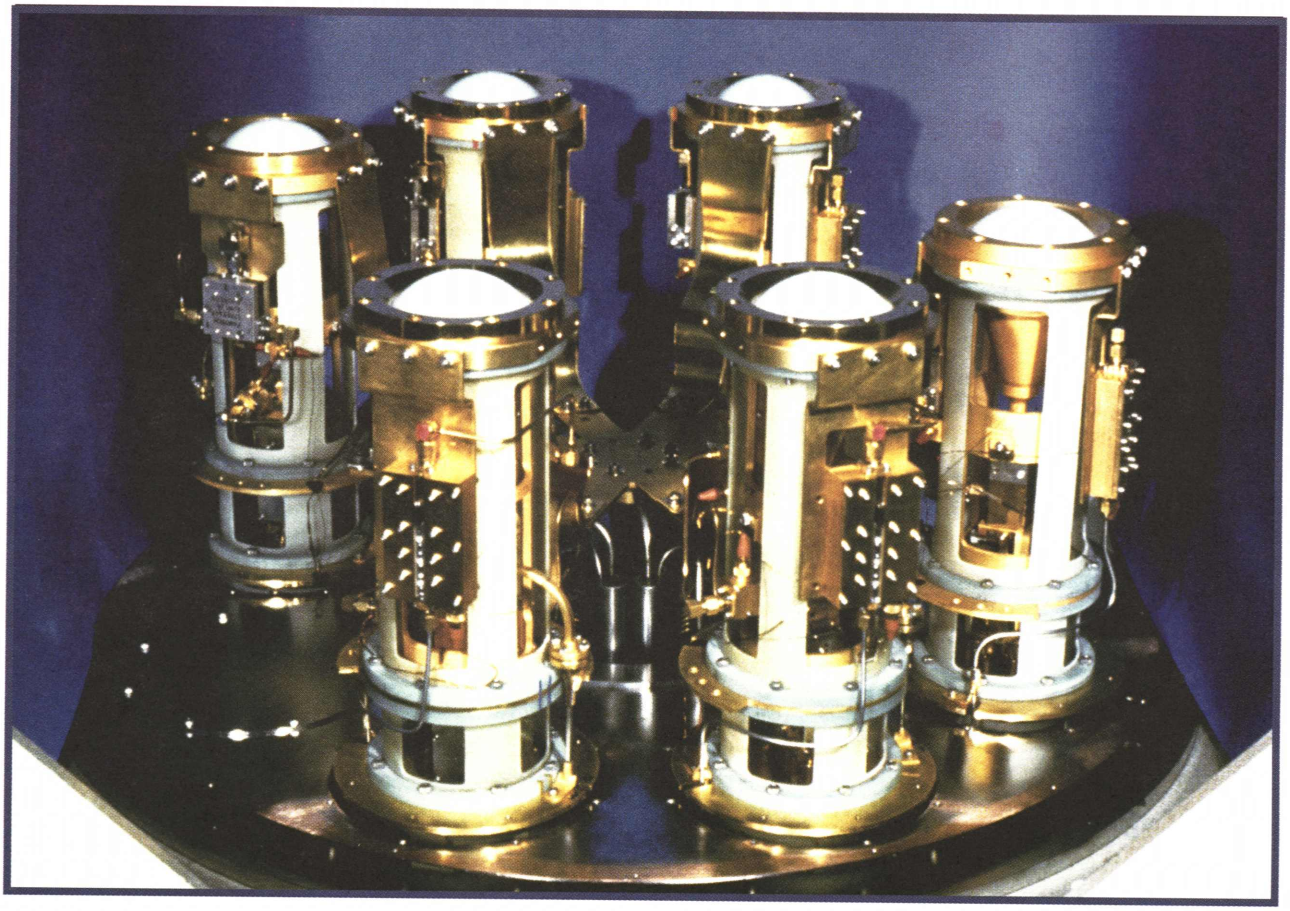
Receivers

The MMA will be equipped with receiving systems which cover completely the frequency ranges of all the terrestrial atmospheric *windows* between 9 and 0.8 mm. Most of the receivers will be built around superconducting tunnel junction mixers which operate at a temperature of no more than 4 degrees above absolute zero. With 40 antennas and approximately 10 superconducting mixers needed to cover the frequency range of each antenna, the MMA will be the most extensive superconducting electronics receiving system in the world. A photograph of a possible multi-band MMA receiver is found below.

Signal Processing Electronics

The MMA forms its images by continuously combining the received signals from each antenna with those from each of all the other antennas. Since there are 780 antenna pairs and the signal from each antenna has a bandwidth of 2 GHz, the signal processing electronics must analyze the signal at a rate of 1.5 THz, more than forty times faster than is achieved by the signal correlation electronics of any existing radio synthesis array telescope.

Engineering design concept of the MMA antenna.



A possible prototype for the MMA receivers. Shown here are six superconducting receivers sharing a common 4K cryogenic dewar.

The MMA — Summary of Instrumental Parameters

Array —	
Number of Antennas:	40
Total Collecting Area:	2010 m^2
Angular Resolution:	$0\rlap{.}''07\lambda_{(mm)}$
Antennas —	
Diameter:	8.0 m
Precision:	$\lambda/40$ at 1 mm
Pointing:	1/20 beamwidth
Transportable	
Configurations —	
Compact:	70 m
Intermediate (2):	250 m, 900 m
High Resolution:	3 km
Frequencies —	
Emphasis on:	195–366 GHz
Broadband Coverage:	30–50 GHz
	68–115 GHz
	130–183 GHz
Versatility:	Simultaneous multi-band operation
Site —	
High-Altitude—suitable for precision imaging at 1 mm	

MMA SITE

The principal MMA site considerations are these: (1) The site must be large enough and flat enough to accommodate a reconfigurable array of 8-meter antennas that at times will be spread over an area 3 km in extent, and (2) the atmospheric opacity at millimeter and sub-millimeter wavelengths is mostly due to atmospheric water vapor, and since water vapor has an atmospheric scale-height of about 1800 meters, the optimum MMA sites are dry and these sites are to be found at high elevation.

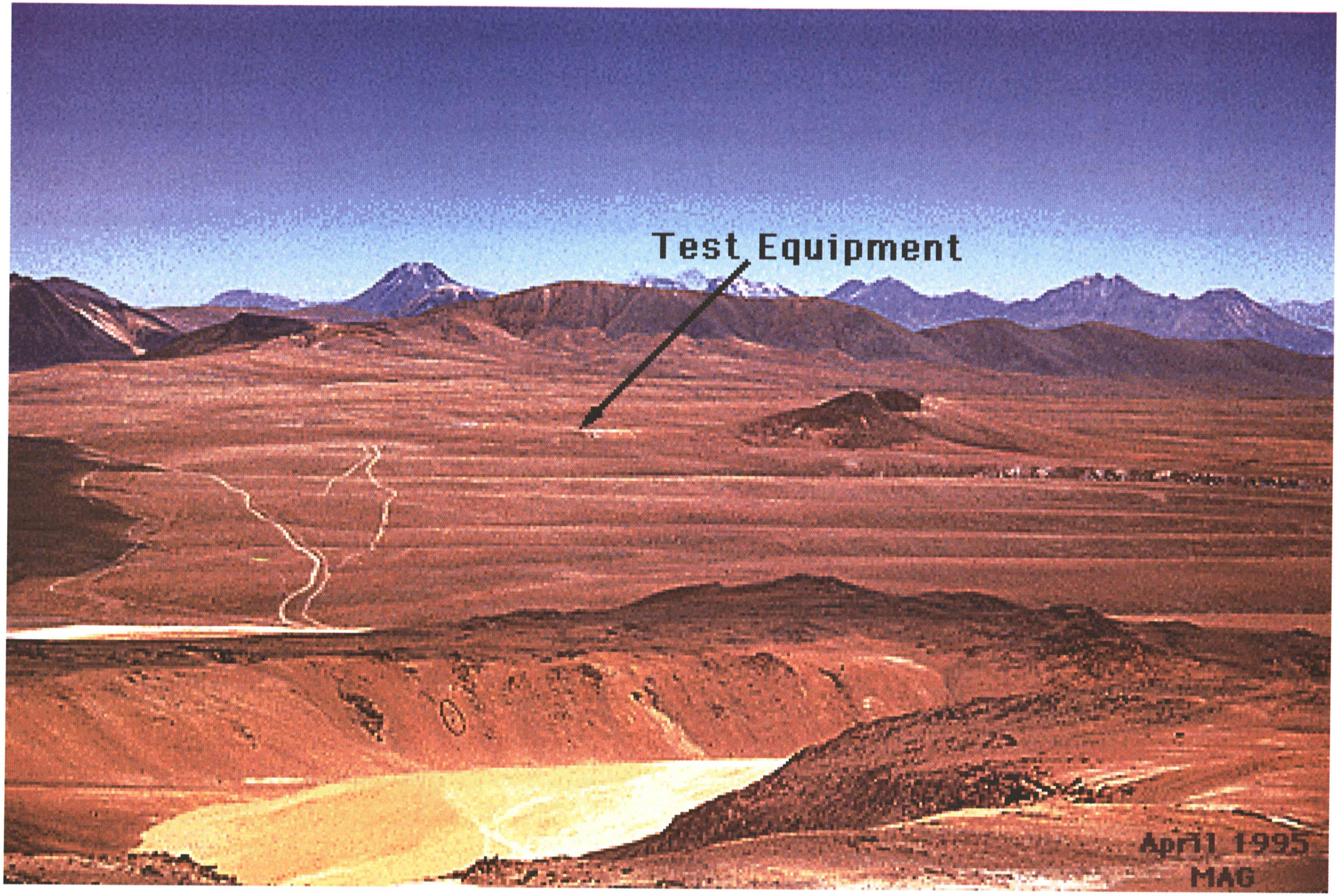
Opacity tests done in the continental southwest of the United States, on Mauna Kea in Hawaii, and in the foothills of the Andes in the northern Atacama desert in Chile indicate that the latter is the more favorable location for the MMA. Tests are continuing on Mauna Kea and on the Chilean site which is shown in the photo on the next page. This area is at 5000 meters (16,400 feet) elevation. The atmospheric tests include measurements of the 225 GHz opacity and of the stability of the atmosphere (the radio *seeing*). For a site as dry as the Chilean site appears to be, 1 mm of precipitable water or less, the atmospheric transparency is excellent in the atmospheric windows between 0.8 and 9 mm (30-350 GHz), and the windows at still higher frequency are also accessible for astronomical obsrvations as shown on the accompanying plot.

Low mean atmospheric opacity, τ, on the site is important because the sensitivity of the array degrades *exponentially* with τ. An excellent telescope demands an excellent site.

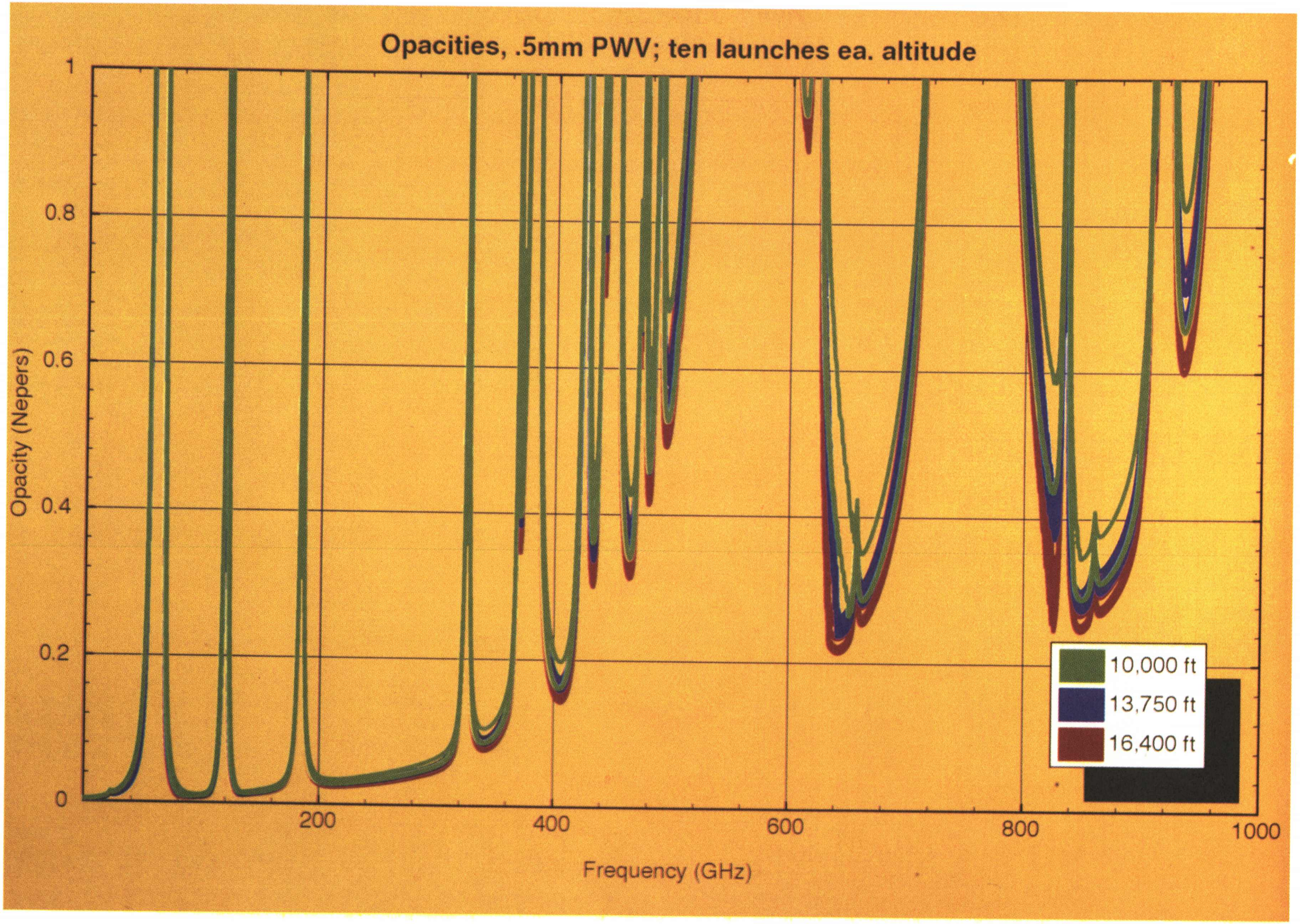
MMA COSTS

A preliminary technical design of the MMA has been completed and refined. It is based on experience in building array and millimeter-wave hardware at the NRAO and on the experiences of other groups involved in telescope projects world wide. On the basis of this preliminary technical design, the capital construction costs for a continental site are estimated at $160M in 1994 dollars. For a site on Mauna Kea, in Hawaii, the estimate is $182M. The costs for a site in Chile are $184M.

The annual operating costs for the MMA are estimated to be, in 1994 dollars, $7.6M and $9.1M for continental and Mauna Kea sites, respectively. The estimate for the operating costs for a Chile site is $7.6M. At least $2.6M for operations is expected to come from foreign partners. Another $2.5M is expected from the closure of the NRAO 12 Meter Telescope on completion of the MMA.



The potential MMA site in northern Chile. The elevation of the site (16,400 feet) assures the very dry atmosphere needed for optimum performance of the MMA.



The atmospheric opacity as a function of frequency to 1000 GHz. This plot is for 0.5mm of precipitable water in the sky above the site as is common on the Chilean site.

MMA: HISTORY OF THE PROJECT

1983 Barrett Committee Recommendations
- Submillimeter Telescope on Mauna Kea (CSO)
- University-Based Instrumentation Program (BIMA; OVRO)
- Design of an Aperture Synthesis Array (MMA)

1984 MMA Design work Begins at the NRAO

1985 MMA Scientific Workshop

1987 MMA Scientific Workshop

1989 MMA Scientific Workshop

1990 AUI Proposal for MMA Submitted to NSF

1991 NSF Astronomy Review of Proposal
- Site Visit
- Mail Reviews

1991 Recommendations of the Bahcall Committee for Major Projects for the Decade of the 1990s
- SIRTF (NASA)
- IR-Optimized 8 m Telescope (northern Gemini Telescope – Mauna Kea)
- MMA
- Southern Hemisphere 8 m Telescope

1992 Astronomy Advisory Committee Endorses MMA R&D Phase

1992 MMA Design and Development Plan Submitted

1994 MMA Development Consortium Formed

1994 MMA Project Development Plan Approved by NSB

1995 Initial Design Funding (NSF/Astronomy)

MMA PROJECT TIMELINE

Year	Milestone	Elapsed Time (years)
1983	MMA Studies Begin	—
1985	MMA Science Workshop	2
1987	MMA Science Workshop	4
1989	MMA Science Workshop	6
1990	Proposal Submitted	7
1991	Proposal Reviews	8
1992	Astronomy Endorsement	9
1994	MDC Formed	11
1994	PDP Approved	11
1995	Initial Design Funding	12
1997	Design and Development Phase	14
1999	Construction Phase	16
2004	Operation	21

MMA PARTNERSHIPS

A project as ambitious, technically challenging, and costly as the MMA requires the participation of those individuals and institutions that have an interest in the success of the project and that have the expertise to contribute that will assure success. Important contributions to the project are being made by university groups in the United States, and plans are in the formative stages in other countries for international involvement in the MMA. We hope to realize no less than 25 percent and no more than 50 percent international participation as outlined below.

Partnerships with U.S. Universities

Millimeter-wave synthesis astronomy was pioneered by the Radio Astronomy Laboratory at the University of California and by the Caltech Owens Valley Radio Observatory (OVRO). The early RAL effort was subsequently broadened to include the University of Illinois and the University of Maryland under the aegis of a consortium called the Berkeley Illinois Maryland Association (BIMA). Individuals associated with OVRO and BIMA are involved in the technical design of the MMA through the mechanism of the Millimeter Array Development Consortium (MDC). The Memorandum of Understanding which constitutes the basis for the MDC is attached. We expect the MDC to play a pivotal role in guiding the development of the project well into its operational phase.

International Partnership

Owing both to the interest of astronomers abroad who are active in millimeter astronomy and to the interest of the NSF in cultivating international partnership in the MMA, we are attempting to define a management structure for the MMA that can expand the project to worldwide scope. A prospectus for international involvement in the MMA (attached) is being circulated. It is an attempt to provide to all international parties a common awareness of the opportunity the MMA presents. It recognizes that some countries may seek capital investment in the project in return for a management voice (MMA Associate) while other countries will prefer access to observing time only but without making a capital contribution and without continuing interest in the details of MMA management and operations. Both forms of participation are of benefit to the project and both may be accommodated as described in the Prospectus.

SOME RECENT MMA QUESTIONS

1. **What are the scientific goals of the MMA?**

The MMA will provide astronomers with the capability to image thermal celestial objects with a resolution superior to that of the Hubble Space Telescope. Scientists will use the MMA to study the formation of galaxies in the early universe before most stars formed. They will investigate the formation of stars and planetary systems with sufficient resolution to discriminate one object from another and to see the chemical composition of each. They will reveal the details of stellar nucleosynthesis by observing the expelled atmospheres of evolved stars and study the cosmic formation of molecules from which we and all life derive.

2. **Why should the MMA be built now?**

Millimeter-wave astronomy and molecular astrophysics had its origin in the United States more than twenty-five years ago. After little more than the first decade of research, it was apparent that high resolution observations were necessary. In response to this need, millimeter-wave interferometric observations were pioneered at Caltech and Berkeley. The MMA, a complete imaging instrument, is the culmination of these efforts and is the instrument recognized as necessary to conduct the scientific research of the future.

The MMA, which provides images of the kinematics and chemistry of gas clouds from which stars, planets, and galaxies form, gives scientists the necessary complement to the next generation of optical and infrared telescopes at a common image resolution. Together these instruments will give scientists the tools to understand the origin and evolution of the heavens. An illustration of the complementary nature of the next generation of astronomical research instruments is given below.

3. **What is the community involvement in the MMA?**

The 1990 AUI proposal for the MMA was a result of three science workshops held at the NRAO in the 1980s. The NSF reviewed the proposal with a site visit committee chaired by Charles Townes. A mail review of the proposal was solicited from twenty-one knowledgeable members of the community. Plans for the MMA were presented to the NSF/NRC committee that planned the decade review of astronomy and astrophysics. The MMA, in competition with many other proposals, was ranked by that committee as the second highest priority major project for ground-based astronomy in the decade of the 1990s (in the Bahcall report).

Subsequent to the Bahcall report, further work on the detailed design of the MMA was begun by the Millimeter Array Development Consortium (MDC), a collaboration of the NRAO, OVRO, and BIMA that involves many of the individuals in the U.S. with experience in millimeter-wave interferometry. We expect the MDC effort to continue well into the MMA construction phase. The MDC is reviewed annually by the MMA Advisory Committee, which is made up of individuals who are not associated with the NRAO nor with the MDC institutions, Caltech, Berkeley, Illinois, or Maryland. Finally, progress on the MMA is shared with the community by means of a monthly teleconference and via regular postings to the World Wide Web on the MMA Home Page.

4. **What technical challenges does the MMA present?**

In order to establish and maintain operations, as a coherent phase-stable instrument at frequencies as high as 360 GHz and on interferometer baselines of 3 km, the MMA antenna must retain its precise figure with varying environmental conditions; a technique must be implemented to correct for atmospheric phase distortions; and the array site and configurations must be chosen such that the array data can be properly calibrated. These are the three principal technical challenges for the MMA, and they are being addressed by the technical working groups of the MMA Development Consortium (MDC). Three years of development work emphasizing construction of prototypes of the antenna and critical instrumentation will precede the actual construction phase of the MMA. The MDC development work will include engineering assessments of the prototype antenna performance as well as a demonstration of the MMA phase calibration techniques as implemented in a prototype form on the existing OVRO and BIMA arrays.

5. **What is the MMA site?**

Evaluations are in progress on both a site in the northern hemisphere, on Mauna Kea in Hawaii, and in the southern hemisphere in northern Chile. The two sites will be compared on the basis of atmospheric transparency, stability, and on cost and operations considerations. The selection of a site, which we hope to make in the summer of 1996, will require an approach to, and successful negotiation with, the appropriate authorities responsible for the site. Astronomers in both Hawaii and Chile have expressed a willingness to help with this process.

6. **What is the cost estimate of the MMA?**

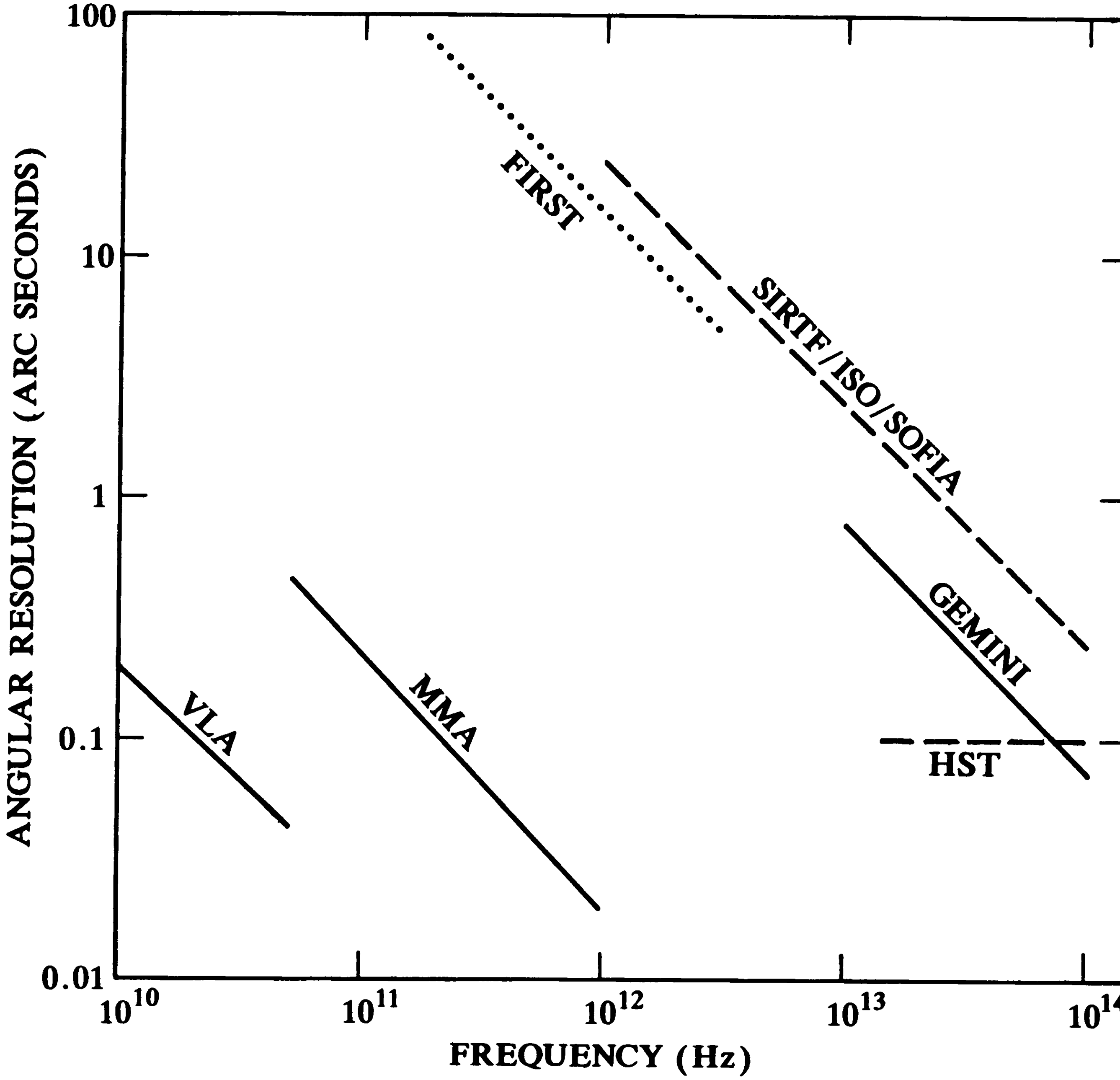
The MMA is estimated to cost approximately $184M on either site under consideration. The NSF is seeking at least 25 percent international participation in the project, and international partners are being sought. Several countries are evaluating options for participation in the MMA, but there are as yet no firm commitments.

7. **How will the MMA be run?**

The MMA will be operated in a manner similar to that of the VLA and VLBA. As is the case with these other two synthesis telescopes, the MMA will be fast: we expect more than 500 scientists will use the MMA annually for their research objectives. It is not necessary for these people to have a large research grant. The goal is to make the MMA cost-effective by providing travel, computing, and ancillary research support for all MMA users in the same manner as is done for the other NRAO instruments. We seek the best science on the array, not science solely by those with the best personal research funding.

8. **What will the MMA cost to run?**

The operating expenses for the MMA on the most expensive site for operations (Mauna Kea) are estimated to be $9.1M (1994$). At least one-quarter of these costs are expected from the foreign partners and another quarter from closure of the NRAO 12 Meter Telescope.



The angular resolution, or imaging detail, shown as a function of frequency, of the major astronomical research telescopes that will be in operation shortly after the turn of the century.