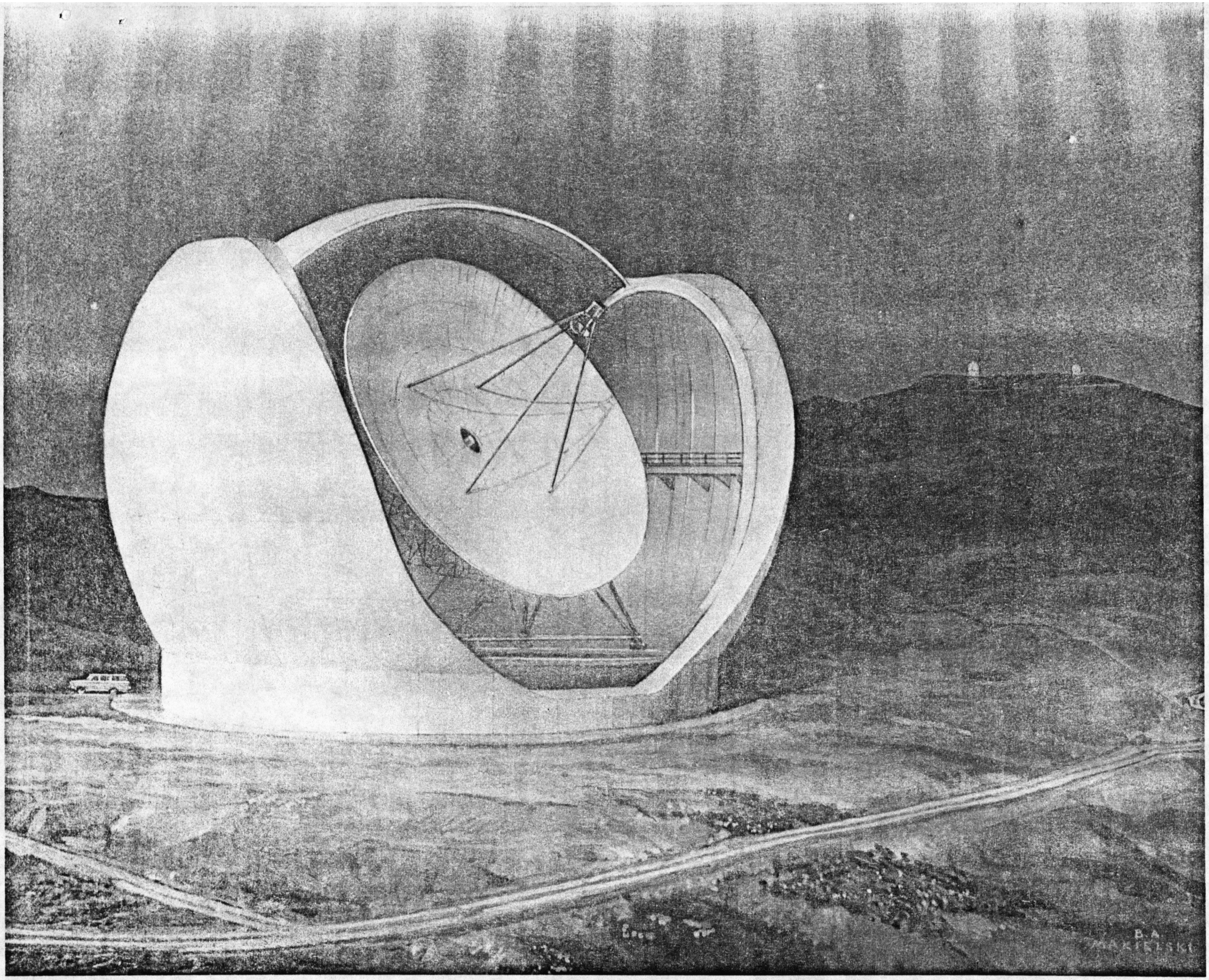
NATIONAL RADIO ASTRONOMY OBSERVATORY

25 Meter
Millimeter - Wave
Telescope

February 10, 1982


B.A.

CONTENTS

I. SUMMARY

Some of the research areas to be addressed by the 25-m millimeter-wave telescope include:

- Star formation and evolution.
- Nucleosynthesis history of galaxies, including our own.
- Physical processes which energize quasars and radio galaxies.
- Formation of the chemical elements and their isotopes.
- The kinematics and structure within galaxies.
- The physical and chemical conditions within the interstellar medium.

The sensitivity and resolving power of the 25-m telescope at wavelengths near and below 1 mm make it ideal for such studies. Even though similar and even larger telescopes are planned or under construction, the combination of surface accuracy, protection from thermal changes (via its astrodome), and location make it a unique instrument in this critical wavelength domain.

Compared to all telescopes completed or now under construction, it will have the highest angular resolution and largest effective collecting area in its important operating wavelength region of nearly a full ocatave from 0.8 to 1.4 mm. This advantage is increased even further because of its southern latitude (which yields more sky coverage) and high altitude site (which significantly reduces atmospheric absorption).

II. A COMPARISON OF THE 25-M MILLIMETER-WAVE TELESCOPE WITH OTHER MAJOR MILLIMETER TELESCOPES

A. The 25-m Telescope

The millimeter-wave astronomy domain consists of a series of "windows," regions where the atmosphere is transparent (non-absorbing), at various wavelengths shorter than 1 cm: at the very shortest wavelengths explored using traditional radio astronomical techniques, about 0.5 millimeter, one is really in the region known previously as the far infrared. At shorter wavelengths the atmosphere becomes progressively less transparent even within the available "windows" due to the presence of precipitable water vapor. Thus, while observations at wavelengths 3-10 mm can usually be done at sea level for some or most months, a dry, elevated mountain site is required to obtain consistently high atmospheric transparency at the higher millimeter-wave frequencies.

Because the millimeter-wave domain is so broad, no one telescope can be designed to be uniformly useful over all of it. Rather, one compromises between the overall diameter of the design and the accuracy of the reflecting surface which can be maintained, in manufacture, setting, and use, over that aperture. Larger telescopes necessarily have less precise surfaces and so work more efficiently at longer wavelengths where surface imperfections, though larger, are nonetheless small compared to the wavelength. Larger radio telescopes have more useful collecting area but not necessarily a higher maximum resolving power, as a smaller instrument can achieve spatial resolution by operating at shorter wavelengths. A small, more precise reflector will operate to shorter wavelengths and will, beyond some well-defined wavelength, have more gathering power than a larger but less precise instrument.

In choosing the design of the 25-m telescope, the NRAO and the millimeter-wave community together sought an instrument affording significant improvements in resolving power, collecting area, and sensitivity to short wavelength radiation. Considered and specifically rejected were a 40-m design useful at wavelengths longer than about 2 mm (largely because it denied the possibility of shorter wavelength observations) and a 15-m design which would have been sensitive to very short wavelength radiation but which would not have afforded increased performance over most of the useful spectrum. In fact, instruments similar to these previously rejected alternatives have been or will be built. The Japanese have constructed a 45-m design, and both Caltech and SRC (England) contemplate erection of 10-15 m dishes on Mauna Kea (Hawaii), which we have chosen as the site of the 25-m telescope. Together with a 30-m telescope under construction near Granada, Spain for use by the French-German consortium IRAM, these instruments will form the backbone of millimeter-wave observations in the Northern Hemisphere for the next twenty years.

B. Performance of the 25-m and Other Millimeter-Wave Telescopes

To place the 25-m design in the context of available and projected millimeter- and sub-millimeter wave instrumentation, we show in Table I the usable collecting area and spatial resolution of a variety of radio telescopes. The 13.7-m U. Massachusetts and 11-m NRAO telescopes are currently in operation (the 11-m has been the major driving force in this field since 1970), and the 45-m Japanese design has just begun use. The 12-m surface, simply bolted on the pier and drives of the older, less precise 11-m, will begin use at the end of 1982 as an interim solution to delays encountered in implementing the 25-m design. The IRAM 30-m project will finish construction by the end of 1982; the 10.4-m CIT instrument has been assembled on their campus.

At wavelengths of 3 mm and longer, where most millimeter-wave astronomy is currently done, the 45-m Japanese instrument has a significant advantage in resolving power but has only slightly larger collecting area than do the next two largest telescopes (the usable area of the Japanese telescope is significantly degraded by surface irregularities at wavelengths shorter than 3 mm)--all three of the larger telescopes represent large gains in performance over the older and/or smaller designs. Although they are smaller, both the 25-m and 30-m designs can achieve higher spatial resolution than the Japanese telescope through the simple expedient of observing at shorter wavelengths. (This is feasible because interstellar molecular species radiate usefully over a broad frequency range.)

Although it is slightly larger than our design, the 30-m telescope will not enjoy a significant advantage in resolution or collecting area at wavelengths of 1.4 mm and less, where it is expected that both instruments will most commonly be used. Because of its high surface accuracy, the 25-m will actually be the single best instrument over the wavelength octave 0.8-1.4 mm, possessing higher collecting area and resolving power than the ultra-precise 10.4-m CIT instrument well into the region where this latter instrument was designed to work. Only at the very shortest wavelengths will this latter instrument be dominant.

C. The Mauna Kea Site and Its Advantages for Use at Millimeter Wavelengths

It was stated earlier that atmospheric conditions are crucial for observation at the shorter-wavelength portion of the millimeter-wave spectrum where the 25-m will be of most use. To avoid compromising the performance of this telescope and to maximize the sky coverage available from the Northern Hemisphere, Mauna Kea (Hawaii) was chosen as the site for the 25-m telescope. The median atmospheric opacity over Mauna Kea is approximately half that at Kitt Peak (the site of our current instrument) and is believed to be the lowest available at any feasible location. Observations at wavelengths as short as 0.5 mm have already been performed on Mauna Kea using existing small optical telescopes.

The purely geographic advantage of the low northerly latitude at Mauna Kea is shown in Table II where the sky coverage at three millimeter-wave sites is compared. Although it yields modest 10-20% increase in coverage of the sky or overall galactic plane, there is much increased access to the center of the Galaxy where much astrochemistry is currently studied and where one has an opportunity to study close-up a galactic nucleus at work.

Table III presents a summary (prepared by J. Baars for the 1981 URSI meeting) of currently operating and proposed millimeter-wave radio telescopes worldwide.

Table I

Resolution and Effective Collecting Area (Area* in m^2; Resolution in Arcseconds)

Telescope	Diameter	2.6 mm		1.3 mm		0.9 mm		0.7 m	
		Area	Resolution	Area	Resolution	Area	Resolution	Area	Resolution
U. Mass.	13.7 m	50	49	--		--		--	
NRAO	11.0 m	36	70	--		--		--	
NRAO	12.0 m	60	56	43	28	26	20	--	
Japan	45.0 m	375	15	--		--		--	
IRAM	30.0 m	350	22	200	11	90	10	--	
NRAO	25.0 m	270	27	210	13	145	9	60	9
CIT (Mauna Kea)	10.4 m	50	65	50	32	50	22	45	17

*Effective Area = 0.6 $\frac{\pi D^2}{4} e^{-(4\pi\varepsilon/\lambda)^2}$, see Table III for values of ε, the surface rms.

Table II

Sky Coverage at Three Millimeter-Wave Sites
(for $\geq$ 10° source elevation)

Operator	Latitude	Fraction of Sky Accessible	Galactic Plane Accessible	Hours/Day on Galactic Center
IRAM	38°	84%	78%	3
Japan	34°	86%	80%	4
NRAO	20°	93%	93%	7

TABLE III

LIST OF MILLIMETER-WAVE TELESCOPES COMPILED BY BAARS, PRESENTED AT THE URSI MEETING 1981 AUGUST

The Major Millimeter Telescopes

	Institute	Location	Year	Height (m)	D (m)	ε (mm)	D/ε (10^3)	λ_{min} (mm)	Remarks
1.	Aerospace Corp.	Los Angeles	1963	0	4.6	0.08	58	1.0	open - source variability
2.	Lebedev Inst.	Crimea, USSR	1966	500	22.0	0.30	73	3.8	open
3.	Univ. Texas	McDonald Obs.	1967	2070	4.9	0.08	61	1.0	astrodome
4.	Calif., Berkeley	Hat Creek Obs.	1968	1050	6.1	0.13	46	1.6	open - NH_3, H_2O
5.	NRAO	Kitt Peak Obs.	1969	1920	11.0	0.14	78	1.8	astrodome - many molecules (CO)
6.	CRAAM, Brazil	Itapetinga	1972	600	13.7	0.34	40	4.3	radome - H_2O (southern hemisphere)
7.	Chalmers Univ.	Onsala, Sweden	1976	0	20.0	0.18	110	2.3	radome
8.	CSIRO, Aust.	Sydney	1977	0	4.0	0.09	44	1.2	open
9.	Bell Labs	Holmdel, NJ	1977	100	7.0	0.10	70	1.3	open - offset paraboloid
10.	Univ. Mass.	Amherst, MA	1978	500	13.7	0.15	91	1.9	radome
11.	Caltech	Owens Valley, CA	1979	1200	10.4	0.035	300	0.5	open
12.	Tokyo Obs.	Nobeyama, Japan	1982	1350	45.0	0.2	225	2.5	open - under construction[3]
13.	MPIfR, Germany IRAM, Grenoble	Pico Veleta, Spain	1982/83	2850	30.0	0.09	335	1.1	open - operation by IRAM under construction
14.	Caltech	Mauna Kea Obs.	1982/83?	4000	10.4	0.015	690	0.2	astrodome - advanced planning
15.	IRAM, Grenoble	Pl. de Bure, France	1983/84	2500	15.0	0.05	300	0.6	open - under design
16.	SRC, England[1]	Mauna Kea Obs.	1986	4080	15.0	0.05	300	0.6	astrodome - under design
17.	NRAO[2]	Mauna Kea Obs.	?	4080	25.0	0.06	420	0.8	astrodome - status uncertain
18.	Ast. Space Res. Cen.	Mt. Korek, Iraq	1985	2100	30.0	0.09	335	1.1	open - copy of Nr. 13
19.	NRAO	Kitt Peak Obs.	1983	1920	12.0	0.07	170	0.9	astrodome - Nr. 5, new reflector

Note: D is reflector diameter, ε is rms reflector inaccuracy, $\lambda_{min} = 4\pi\varepsilon$.

1. Changed from the Canary Islands in Baars' summary. Telescope and dome currently under reconsideration to accommodate financial burden of locating in Hawaii. This instrument will be operated by a British-Dutch consortium.

2. Entries slightly revised from Baars' summary.

3. Currently operating at 4-mm wavelength.

III. THE SCIENCE REQUIRING A SENSITIVE, HIGH RESOLUTION MILLIMETER-WAVE TELESCOPE--THE 25-m TELESCOPE

Contemporary studies of the evolution of many objects in the universe--the life cycles of giant molecular clouds in our galaxy; the formation of new stars through condensations of gas and dust in these clouds; the aging of stars as reflected through mass-loss and passage to planetary nebulae; the nucleosynthesis history of galaxies; the brightening or dimming of the non-thermal luminosity of the energetic quasars and active galactic nuclei which follows from acceleration or decay of relativistic particles; and even the largest-scale mass-structures of the universe, galaxy clusters--provoke questions which can best be addressed by observations made at millimeter wavelengths. These questions are all the classical ones of astrophysics: how stars are formed, how the chemical elements and their isotopes were formed, the life and death cycles of stars, the formation and structure of galaxies, and the physical processes that energize the quasars. Additionally, the new field of astrochemistry was spawned by the discovery of many organic molecules in the millimeter-wavelength region of the spectrum, and these molecules continue to provide the only probes of the cooler, denser components of the interstellar medium, those that ultimately form stars and planetary systems.

A. Star Formation: The Birth and Death Cycles of Stars

Fundamentally new light has been cast on every phase of the formation and evolution of stars by millimeter-wavelength observations of interstellar molecules.

1. The General Picture of Star Formation.

Dense molecular clouds are now known to contain imbedded core regions of even higher density, which are the sites of imminent star formation. These condensed structures, together with the parameters that describe the typical clouds in which they occur, have revealed for the first time a picture in which stars form, singly or in clusters, possibly through chain-reactions, within giant molecular clouds which are subsequently disrupted into fragments by the new-born stars, only to coalesce later and elsewhere into the next generation of clouds which give birth to more stars. This much has been revealed by existing small telescopes with their modest resolutions. What is missing are the details of the final collapse of the cores into stars--how excess angular momentum and turbulence are dissipated, how much additional fragmentation occurs before stars form; indeed, what is the basic efficiency of forming stars and what determines the mass distribution of the stars. In addition to these questions, we know little about whether triggering mechanisms for collapse (e.g., supernova blast waves, spiral density wave shocks, and HII region shock fronts) are more efficient than self-gravity in forming stars, and whether the initial mass distribution of the stars depends on which mechanism is at work. All of these unanswered questions await observations with larger telescopes and improved spatial resolution.

2. Early Evolutionary Phases of Stars and Their Interactions with Their Surroundings.

Recent molecular observations have revealed an important new phenomenon at the limit of current instrumental resolution--the fact that many types of objects (Herbig-Haro objects, T-Tauri stars, and biconical nebulae), all associated with the earliest phases of star birth, are interacting strongly with their surroundings via powerful stellar winds. These energetic mass outflows have fundamental consequences for existing theories of stellar evolution and provide a strong energy input into the surrounding cloud medium which may well be decisive in determining the subsequent evolution of the cloud (whether it can continue to collapse and form more stars, for instance) or, on a larger scale, on the dynamics and energy balance of the interstellar medium as a whole. Important details of these winds are lacking because of inadequate wavelength coverage and spatial resolution. High-excitation molecular emission lines (which occur at the shortest wavelengths) need to be observed to determine if these flows are optically thick and, therefore, how much energy and mass is being transported. Higher resolution is needed to detect these winds in more distant and lower-mass objects to get an overall picture of this phenomenon. In particular, the high-velocity wings observed in the molecular lines of many molecular clouds may all arise from stellar winds; very high mass loss rates are implied if this is the case.

3. Mass Loss and Terminal Stages of Evolved Stars.

Massive evolved stars are also known to lose mass to the interstellar medium via strong stellar winds. The chemical composition of the interstellar medium may be largely determined by this input since all of the heavier elements beyond helium, as well as their isotopes, are formed by nucleosynthesis in stars. The importance of the mass loss from evolved stars upon the energy balance of the interstellar gas is largely unknown, since quantitative study of the rates of loss can only be performed presently on a few nearby such objects. This mass loss is best studied by means of molecular lines at millimeter wavelengths because only these convey vital kinematic and other physical information and can penetrate the dense, opaque circumstellar shells of gas and dust that surround these evolved stars.

Even with limited resolution, a new picture of post-main-sequence evolution has emerged through millimeter-wavelength studies of nearby evolved stars with angularly resolved circumstellar shells. Through molecular studies it appears that, for the first time, one can trace an evolutionary sequence which starts with luminous cool carbon-rich stars that form circumstellar shells of dust and gas; these stars evolve along the horizontal branch of the H-R diagram toward earlier spectral type, passing first through a bipolar reflecton nebular stage, then to a hotter stage which initially ionized the inner part of the shell and produces a compact planetary nebula, thence to a larger ionized region, and finally a bona fide planetary nebula. This picture is currently based on only a few nearby objects. Larger telescopes will allow many more distant objects in these phases to be detected, thus putting this picture on a firm basis.

Of singular importance to theories of evolution of late-type stars are the details of just how mass outflow occurs. Is it continuous or does it occur in bursts? These two possibilities can be distinguished by detailed knowledge of the distribution of density in the circumstellar shells, but this requires much better spatial resolution than is afforded by current telescopes.

II. CHEMICAL ISOTOPES: CLOSURE OF THE UNIVERSE, AND THE NUCLEOSYNTHESIS HISTORY OF GALAXIES

According to the Big Bang origin of the universe, only the elements hydrogen and helium and their isotopes (including deuterium) were produced primordially and in ratios which can be related theoretically to the current mass density of the universe. The value of this current density dictates whether the universe is closed or open.

All other chemical elements and their isotopes are synthesized in stars, so that the present interstellar abundances of carbon, oxygen, nitrogen, and their isotopes depend on rates of star formation, the stellar mass distribution, nuclear processes within stars, and rates of mass loss of stellar material back into the interstellar medium. Estimates of each of these factors exist, but knowledge of the isotope ratios in particular will be a decisive test of our understanding of these fundamental astrophysical problems.

The study of molecules at millimeter wavelengths has provided unique estimates of the deuterium to hydrogen ratio, central to the cosmological problem, and of the isotope ratios of carbon and other elements, which bears on the nucleosynthesis history of our and other galaxies. Such millimeter-wavelength studies of molecules are unique for these studies because one must be able to trace the run of isotope abundances across the galaxy in order to take account of known differential effects arising from different stellar populations in different parts of the galaxy. UV and IR studies of the chemical elements and their isotopes are restricted to local regions because of the obscuration of the interstellar medium.

Unfortunately, chemical fractionation, arising from certain processes at work in the formation of the molecules, serves to confuse these issues at the present time. In order to separate the purely chemical effects from those fundamental to cosmology and nucleosynthesis, we must know more accurately the physical conditions on small scales within molecular clouds in order to be sure that such small regions are not dominating the chemical effects we observe with currently limited resolution. In addition, accurately determined abundances are derivable only by study of several emission lines from the molecules involved, and these involve wavelengths of 1 mm and often shorter, beyond the limits of existing telescopes.

The limited resolving power of current telescopes has not permitted the study of these intriguing questions in galaxies outside our own, with the exception of a single measure of a carbon isotope ratio in the galaxies M82 and M31. These measures suggest intriguing differences from our own galaxy. Larger telescopes operating to shorter wavelengths are needed to address the fundamental question of whether the nucleosynthesis history of our galaxy differs from others.

III. THE MOLECULAR CONTENT OF GALAXIES

Detailed surveys of our own galaxy have shown that the interstellar gas, which comprises 10% of the galactic mass, is itself 50% molecular on average and in some regions (the large "molecular ring") as much as 90% molecular. Further, the molecular gas resides in giant molecular clouds which are the most massive entities in the galaxy. As such, they have a decisive effect upon the dynamics and kinematics not only of the overall interstellar medium but also upon the stellar populations which feel their gravitational effects. Because we cannot see our galaxy in overall perspective, one central question remains unanswered: What is the spiral pattern in our galaxy and how does it relate to such patterns seen in many other galaxies?

Observations of the molecular gas in other galactic systems made with the currently limited telescopes are unable to tell us much except that, in a blurred sense, many galaxies exhibit molecular contents comparable to that of our own galaxy. One of our most fundamental notions is that stars are formed from dense molecular clouds; thus if stars are observed to lie in spiral patterns in other galaxies so should the distribution of molecular gas. Unfortunately, existing telescopes lack the resolving power to answer this possibility. The question goes beyond merely a test of this fundamental notion. If we can, with sufficiently large telescopes, measure the sizes and velocity patterns of molecular clouds within and between spiral arms, we can test the central theory of how spiral arms form and are maintained in galaxies, because this theory predicts that spiral-patterned shock waves, produced by the observed distributions of stars, should compress the interstellar gas into giant molecular clouds in spiral patterns; these clouds in turn are the birth places of massive young stars which therefore adopt and maintain the basic spiral structure.

Although we cannot, with current telescopes, study the overall distribution of molecular gas very accurately in other galaxies, there is some suggestion that the giant ring-like molecular structure seen in our galaxy is unique, a surprising and disturbing conclusion. We can also dimly tell that galaxies seem to divide into two types, those whose molecular gas is confined heavily to the nuclear regions and those where it is spread out over a disk-like configuration. The dominant role of the molecular gas in our own galaxy certainly suggests that we have much to learn about how other galaxies of various types formed and evolved if we can suitably refine our knowledge of their molecular content. The answer lies with much larger millimeter-wavelength telescopes.

IV. INTERSTELLAR CHEMISTRY

The discovery at millimeter wavelengths of numerous (54) molecular species in interstellar clouds has spawned a new field of astronomical and laboratory research--astrochemistry. The need is to understand the formation and ion-molecule chemistry of these species, some of which were identified by astronomers prior to their synthesis in the laboratory and to elucidate the role they play in furthering the evolution of interstellar clouds.

Further understanding of this chemistry requires instrumental advances toward both shorter wavelengths and higher spatial resolution. Many important atoms and molecules radiate only at wavelengths shorter than current telescopes of adequate size can reach. A prime example of the fundamental science awaiting us in the sub-millimeter region is the recent discovery at 0.61-mm wavelength of interstellar atomic carbon. This species is not only central to most interstellar molecular chemistry (40 of the 54 known interstellar molecules are organic) but is a powerful cooling agent which may well dictate the fundamental energy balance in the outer regions of interstellar clouds. Carbon was discovered and subsequently studied with small telescopes (both airborne and on the excellent Mauna Kea site). To understand its central role in interstellar chemistry requires study with much higher resolution. If the current inexplicably high abundances derived for atomic carbon from the present poor-resolution data should prevail, major adjustments in our present concepts of interstellar chemistry will be necessary.

Other entire classes of molecular species are observable only at sub-millimeter wavelengths, notably the hydride molecules containing phosphorous, calcium, magnesium, sodium, and other elements not observable in any other form in dense molecular clouds. An important current field of research is that of the depletion of elements in the interstellar medium (by condensation onto dust grains), begun at ultraviolet wavelengths by the Copernicus satellite in highly diffuse clouds, but requiring molecular observations at millimeter wavelenghs to penetrate the dense clouds where the depletion effects will be pronounced. Among the most heavily depleted elements appear to be those just mentioned.

Another important class of compounds, presently beyond possibility of detection, are the highly refractory compounds (MgO, FeO, CaO, SiC, PN) which are fundamentally important to current theories of interstellar grains, but which may occur in the gas (observable) phase only under highly energetic conditions which will involve high temperatures and small regions. High temperatures mean the shortest-wavelength transitions radiate most strongly while small regions demand the highest spatial resolution.

Circumstantial evidence currently favors shock-induced chemistry as an important aspect of the dense, hot cores of many molecular clouds, notably the cores of the Orion and galactic center clouds. It is entirely possible that most of the more complicated molecular species presently observed owe their existence primarily to high-temperature shock chemistry. The evidence is particularly compelling for regions displaying powerful maser emission from several molecular species (OH, H_2O, SiO). Shocked regions of high temperature are small in size, and the highest possible resolution is needed for them. Again, high temperatures also favor the shortest wavelength lines.

With the resolution afforded by the 25-m, one may even test whether protostellar nebulae are significant sources of interstellar molecules, as was suggested a decade ago. Such an origin may be required to explain the more complex molecular species which have not been adequately explained in the framework of the ion-molecule chemistry. Evidence from carbonaceous chondrites suggests our proto-solar system was an efficient synthesizer of organic molecules which later escaped to interstellar space. Many solar-type stars are presently forming in nearby molecular clouds and may well be dispersing molecular material into the cloud. Within these nearby clouds, the 25-m telescope could resolve regions whose size is only 40 times the present solar system and thus test this possible origin of interstellar molecules.

V. EXTRAGALACTIC RADIO SOURCES

Among the most fundamental of all questions in astrophysics is the nature of the engine that drives the powerful emission from quasars and active nuclei of galaxies. The millimeter and submillimeter-wavelength region of the spectrum is potentially decisive in understanding these problems.

In the extended extragalactic sources, which are usually associated with galaxies, it is at millimeter wavelengths that the synchrotron radiation lifetimes of electrons become less than the times required for the relativistic electrons to cross the radio lobes. Thus maps of the spectral index at sufficient resolution will distinguish injection mechanisms from *in situ* acceleration models for replenishing the energetic electrons. For most such sources, spectral indices are similar, implying similar physical conditions among the sources. Any important differences will be revealed much more clearly at millimeter wavelengths.

Compact extragalactic sources (associated with QSOs and nuclei of galaxies) are at present poorly observed at millimeter wavelength because of lack of sensitivity of current telescopes. Among the few strongest that are detectable at 1 mm, the core regions produce most of the emission. In some cases the spectral index is still rising at 1 mm. Time variations of the optical emission are often not correlated with those in the radio emission, contrary to theory. Observations of many such sources are needed to determine at what wavelength the theory breaks down (millimeter or sub-millimeter). Radio-quiet QSOs also need to be observed at millimeter wavelengths with high sensitivity, since it is possible that their maxium emission may occur in the millimeter or sub-millimeter-wavelength region. Finally, for all compact sources it is the shorter wavelengths that sample the higher-energy electrons and thus place the tighter constraints on all theoretical models.

VI. LARGE-SCALE STRUCTURE OF THE UNIVERSE

Continuum observations at millimeter wavelengths provide a unique probe of the universe as a whole, both as it is now and as it appeared at the earliest epochs observationally accessible to us. For instance, X-ray observations of clusters of galaxies tell us that uncondensed matter is present, and they tell us the temperature of that material. Millimeter-wave observations of a depression in the microwave 3 K background seen toward these same clusters tells us the distribution of intracluster matter; hence the X-ray and millimeter-wavelength observations together provide a complete picture. A unique solution of the distribution of density and temperature in the intracluster medium requires, however, precise (high resolution) mapping of the cold spots at both millimeter and X-ray wavelengths.

NATIONAL RADIO ASTRONOMY OBSERVATORY

The Twenty-Five Meter
Millimeter Wave Telescope

Prepared for NRAO presentation to the NSF
February 6, 1981

NOTE THAT THIS IS ONE YEAR OLD
AND SOME REFERENCES TO THE 36-FOOT TELESCOPE
ARE DATED BECAUSE OF THE CURRENT RESURFACING.

RATIONALE FOR
CONSTRUCTION OF THE 25-METER MILLIMETER WAVE
TELESCOPE AT MAUNA KEA

1. WHY DO YOU WANT TO BUILD THE 25-METER MILLIMETER WAVE TELESCOPE?

   Because of the important discoveries this part of the spectrum offers: molecules in space, star formation, isotope studies are just a few. Our plans represent the natural and vital growth of a field of science pioneered in this country. The combination of sensitivity and wavelength coverage attainable with this instrument will open new vistas in the description and understanding of the Universe.

2. WHY IN A TIME OF TIGHT BUDGETS DO YOU WANT TO BUILD A NEW FACILITY, SPECIFICALLY THE 25-METER TELESCOPE?

   Astronomy is largely an observational rather than an experimental science--controlled experiments under laboratory conditions are rarely possible. Progress depends on construction of clever and unique instrumentation which will enable us to collect and analyze the small number of incoming photons from which we build our view of the Universe.

   The 25-meter telescope is proposed as the best way to exploit the achievements of the previous ten years in mm-wave astronomy, a field which originated in the U.S. and has become one of the most active and rapidly developing areas in science. Techniques are now available to build a new advanced facility at a uniquely suited site (Mauna Kea) so as to replace an aging 36-foot (11-meter) telescope on Kitt Peak and thereby maintain a first-rank capability for the general use of the astronomical community. With the operation of the 25-meter, the 36-foot telescope would be phased out and its operating costs made available for the 25-meter.

3. WHAT WILL THIS TELESCOPE DO THAT OTHER U.S. FACILITIES CANNOT?

   This telescope has the <u>combination</u> of both high sensitivity and precision for operation at millimeter wavelengths. Further, it will be located at an ideal site for such observations. It is this combination that will make it unique. Other facilities in this country, mostly university operated, are a necessary adjunct for student training and for university based research. The existence of a nationally-operated 25-meter telescope will make available a state-of-the-art instrument for those unique experiments which are not possible at smaller facilities.

In brief, this telescope offers the combination of sensitivity, frequency coverage and unique site that no other telescope will match.

4. HOW DOES THE 25-METER TELESCOPE COMPARE WITH OTHER FOREIGN MILLIMETER FACILITIES?

There are major millimeter telescopes completed or under construction in Japan, Spain (built by Germany), and Sweden. Smaller facilities are planned by other countries.

In the roughest sense this telescope is comparable to others, especially the largest, such as those being built by Germany and by Japan, though in both cases we know that the U.S. 25-meter surface accuracy will be better. However, an important factor is the site for the 25-meter, namely Mauna Kea at an altitude of 14,000 feet and a latitude of 20°. These geographical advantages will give us far less problem with atmospheric water vapor; the southern latitude will allow us to see a much larger part of the southern sky which contains the direction to the center of our Galaxy as well as a significant portion of the Milky Way.

5. WHY ARE WE BUILDING A SMALLER ANTENNA WHEN THE GERMANS AND JAPANESE ARE BUILDING LARGER ANTENNAS?

We are building a smaller telescope because from our engineering studies we feel that this represents the optimum of the <u>combination</u> of size and surface accuracy, the latter allowing short wavelength operation. We firmly believe that our telescope will be the largest short wavelength instrument in the world and sited at a truly unique location.

6. WHY BUILD THIS TELESCOPE WHEN THERE IS QUITE A LARGE ONE AT THE UNIVERSITY OF MASSACHUSETTS AS WELL AS THE NATIONAL FACILITY'S 36-FOOT AT KITT PEAK?

The history of astronomy is built on the development of initially small instruments. As these instruments are pushed to their limits new major breakthroughs are made by building larger, more sensitive telescopes. In the case of the 25-meter, there will not only be a significant increase in the collecting area but an improvement in the wavelength coverage of a full octave over our national facility 36-foot telescope as well as the 45-foot telescope at the University of Massachusetts.

7. HOW DOES THE 25-METER COMPARE WITH THE PRECISION 10-METER TELESCOPES CONSTRUCTED BY LEIGHTON AT CALTECH?

The 25-meter will be the largest feasible antenna that can efficiently operate to a limiting wavelength of about 800 micrometers. Smaller antennas, such as Leighton's, can be built to go to even shorter wavelengths and there are transmission windows in the atmosphere that call for such observations. Leighton's work is pioneering the development in that particular area. Optical telescopes represent the extreme of this case. They are designed to work at a fraction of a micrometer, but their size is much less (4 to 5 meters for the largest).

8. THIS TELESCOPE IS DESCRIBED AS A FOREFRONT INSTRUMENT. HOW FOREFRONT WILL IT BE IN 1985, 1990?

With authorization and initial funding in 1982, the construction plans are such that the telescope will be completed for use in 1985. At that time it will clearly be at the forefront of millimeter radio astronomy in its own right as well as in comparison to other telescopes now planned or under construction elsewhere in the world. Its unique capabilities and site will keep it so for a generation into the future.

9. DO YOU THINK YOU CAN MEET THE CONSTRUCTION SPECIFICATIONS THAT YOU HAVE SET FOR YOURSELF?

Extensive engineering studies for the design of this telescope have been made for a number of years, and we are confident that, in the light of our previous construction experience, the specifications can be met within the budget estimate. If anything, we believe we are conservative in our design goals.

10. HOW WILL THE 25-METER TELESCOPE DIFFER FROM THOSE AT THE U. MASSACHUSETTS OR AT KITT PEAK?

The millimeter-wave telescopes, such as those at Kitt Peak or at the University of Massachusetts, do not go to as short a wavelength as this antenna nor do they have the collecting area of the 25-meter. Observations in an entirely new spectral window will be available as well as greatly enhanced sensitivity. Both of these vital aspects will be further enhanced by the superior atmospheric conditions available at Mauna Kea.

11. WHY CAN'T THIS PARTICULAR PROJECT BE POSTPONED FOR SEVERAL YEARS?

We have the technical know-how, the staff and the momentum of the community to build this telescope now. The technical description was completed and submitted to the Foundation in 1975. Detailed planning has been continually made. During this period the astronomical community has designated this project for the highest priority for major new facilities, in part because the science needs such a facility, in part because the 36-foot will soon cease to be a competitive instrument.

The development, the growth, the lead that we have in millimeter radio astronomy will leave us to be taken up by other research groups elsewhere in the world. Unless new projects in science are maintained, future generations of our young scientists and engineers will be denied the opportunity to partake in a meaningful manner in this vital area of research. Continued delay will see the scientists, engineers, and technicians who are vital to the success of the 25-meter project turning to other endeavors.

12. WHAT HAS BEEN THE IMPACT OF MILLIMETER-WAVE ASTRONOMY ON ASTRONOMY IN GENERAL?

The impact of millimeter wave research has been overwhelming. Not only within the astronomical community but also in the broader areas of physics, biology and chemistry, e.g., new and important chemical species, unknown in terrestrial laboratories, have been identified in space; new reaction mechanisms have been developed for chemistry; the organic chemistry discovered in space has altered the view of the earth's primordial environment. It therefore has become an important vehicle for interdisciplinary exchange and research.

13. DO YOU EXPECT THIS RAPID DEVELOPMENT TO CONTINUE WITH THIS NEW TELESCOPE?

Yes. Witness the broad support for its construction within the astronomical community.

14. DO YOU HAVE PLANS FOR ADDITIONS OR IMPROVEMENTS FOR THIS TELESCOPE THAT WOULD REPRESENT A MAJOR NEW INVESTMENT?

Scientific research continually evolves. We can envision additions and improvements, some of them minor, occurring in the natural development of the field. We can also envision major additions, such as a small auxiliary antenna, being made to the facility for different types of research experiments.

15. YOU HAVE JUST COMPLETED THE VLA. THOUGH MUCH IN USE FOR ASTRONOMICAL RESEARCH, IT IS NOT YET FULLY OPERATIONAL. WHY DO YOU WANT TO BUILD ANOTHER TELESCOPE NOW?

The very success of the VLA as a research tool shows the vitality of astronomy. We are suffering from success in that our data analysis is running behind our data acquisition. This has not lessened the demand for the instrument and major data analysis improvements are continuously being implemented. The type of science for the two instruments is completely different: The VLA yields high-sensitivity, high resolution maps in the centimeter-wave region of the spectrum; the 25-meter will be used at completely different, shorter wavelengths. In some cases these data will complement one another, in others information gathered will refer to different aspects of the Universe.

16. WHY DID YOU CHOOSE MAUNA KEA AS THE SITE?

Mauna Kea possesses the unique combination of favorable weather patterns, unmatched atmospheric transparency, and a relatively southerly geographic latitude which will render access to regions of the sky previously studied only from the Southern Hemisphere. It is in fact the southern-most site available within the United States. This site is already developed and contains a half dozen optical telescopes.

17. IS THE EXTRA EXPENSE FOR CONSTRUCTION AND OPERATION AT MAUNA KEA WORTH IT?

Building and operating the 25-meter on Mauna Kea will cost more. However, it is important to realize that many of the new optical, infrared and millimeter facilities in North America have been built or are being planned for Mauna Kea. Not only by American research teams but also by foreign groups. The reason is simple: the best science can be done from that location. In brief, yes, it is worth it.

18. ARE THERE OTHER SITES THAT ARE POSSIBILITIES FOR SUCH A FACILITY?

Yes, other sites do offer possibilities for millimeter observations and many were considered, with several of the better ones examined in great detail. The net result of this lengthy, careful study was that Mauna Kea offered the best location by far, with no other being close in all the necessary parameters of support and the science that could be done from Mauna Kea.

19. ARE THERE PARTICULAR PROBLEMS UNIQUE TO THIS HIGH ALTITUDE AS FAR AS CONSTRUCTION IS CONCERNED?

Working at high altitudes is more difficult, but other facilities, the three most recent being the NASA infrared telescope, the United Kingdom infrared telescope, and the Canadian-French-Hawaiian consortium telescope, were all built essentially on time and within or close to budget. Clearly such major construction can be performed at these high altitudes.

20. WHAT ARE THE RELATIONSHIPS BETWEEN THIS NATIONAL FACILITY AND THE UNIVERSITY OF HAWAII AND THE STATE OF HAWAII?

The Mauna Kea mountaintop is operated as a science reserve by the University of Hawaii through arrangements with the appropriate state organizations. The telescope will be located on land rented from the State. The University of Hawaii has an Institute of Astronomy which has been our liaison with the various state officials who have been aiding us in the preparation of plans for locating at such a site. Cooperation has been extended not only from the University administration, from the President on down, but also from state officials, including Governor Ariyoshi. Locating in any new site and state brings with it new problems, and we expect such problems which may be peculiar to Hawaii to arise, but we see no major reason for concern on this issue.

21. WHAT ARE YOUR PLANS FOR THE 36-FOOT ANTENNA, VIS-A-VIS, THE CONSTRUCTION OF THIS TELESCOPE?

We do not intend to continue operating the 36-foot antenna at Kitt Peak. It will be made obsolete by this 25-meter. The 36-foot operating expense will be used to partially offset the higher expenses for operation of the 25-meter.

22. WHERE WILL THE MONIES FOR THE OPERATION OF THIS TELESCOPE COME FROM?

Approximately one-half of the operating expenses at Mauna Kea will be available from the closing of the NRAO Tucson facility. The additional monies, to cover the higher expenses of operating in the Hawaiian environment, will be requested from the NSF. Part of this in FY 1984 and the full additional monies in FY 1985.

23. CAN NRAO OPERATIONS IN GENERAL ABSORB THIS NEED FOR EXTRA MONIES?

No. Our budgets to date (1981) have been lean; they have not kept pace with inflation. We do not envision reductions beyond the closing of our Tucson facility.

24. WHAT WILL THIS TELESCOPE DO FOR THE ECONOMY IN HAWAII?

The approximate operating staff for the telescope will be 30 people. Of the overall operating expenses, $3 M in 1985, approximately half will be in salaries to the personnel located in Hawaii. Perhaps an additional 20% would be spent for support, supplies and material that would come from Hawaii.

25. WHAT WILL BE THE IMPACT ON RADIO ASTRONOMY WITHIN THE UNITED STATES IF THIS TELESCOPE IS NOT BUILT?

The task of the national observatories is to supply unique instrumentation to the astronomical community. Such instrumentation is generally expensive and only one of a kind can be afforded by the country. If the 25-meter is not built we will expect to see a great lessening in the development of short-wavelength radio astronomy with only a few pockets of research at those universities which have their own instrumentation. As noted earlier, this instrumentation is always smaller and with only one exception of less precision than the 25-meter In summary, we would expect an entire area of research in the radio spectrum to diminish within this country. American astronomers do use foreign facilities, but generally these facilities are of limited availability to the American astronomical community.

26. COULD WE EXPECT THE MILLIMETER COMMUNITY TO GO TO GERMANY, OR JAPAN?

The operating policies at the foreign millimeter installations have not been set as yet. Americans have used the millimeter telescope in Sweden. It is much smaller than the German and Japanese telescopes.

27. ISN'T THE NUMBER OF ASTRONOMERS SMALL?

Relative to many other sciences, yes, their number is small. However it is their work that gives us the picture of the entire Universe. Further, it must be appreciated that astronomers do not have what we would think of as a laboratory in which to perform an experiment. To carry on scientific research requires major observatory facilities, facilities such as the 25-meter telescope.

28. WHAT SPINOFF OR BENEFITS MAY OR HAVE ACCRUED TO AMERICAN TECHNOLOGY FROM MILLIMETER WAVE ASTRONOMY?

There is no question that millimeter radio astronomy has pioneered in the opening up of this part of the electromagnetic spectrum. This is an area now being developed extensively by the military and the communications industry. That is not to say that such development would not have occurred without radio astronomy, but some of its basic developments have been made at radio astronomy facilities. As examples:

(1) Behavior and design of Schottky-barrier semiconductors;
(2) Diode fabrication for mm-wave use;
(3) Extreme-sensitivity mixers at mm-wavelengths;
(4) Extreme-sensitivity solid-state amplifiers at C-band;
(5) Cavity-design for millimeter-wave mixers;
(6) Frequency doublers and triplers at mm-waves;
(7) Phase-locking of millimeter-wave klystrons; and
(8) Quasi-optical techniques: local oscillator injection; polarizers; mixer image rejection; precise, high-rejection bandpass filters.

Radio astronomy has also aided in the study of the atmosphere and some of its contaminents.

29. HAVE YOU CONSIDERED FOREIGN COOPERATION IN BUILDING THIS FACILITY?

Foreign cooperation in building large millimeter facilities was considered early in the history of these major new developments. However, the course of events has been such that the countries involved decided to develop their own facilities. There is a complex arrangement for administrative cooperation between the French and Germans but each is building its own telescope, sharing only a laboratory in France.

The 25-meter is of a size and cost that single country funding is not only feasible but is also the most cost effective for construction and operation. Further, the U.S. demand is sufficient to fully occupy the use of such a facility.