MILLIMETER ARRAY
MEMO NO. 9

Report of

Subcommittee on Millimeter- and Submillimeter-Wavelength Astronomy

National Science Foundation
Astronomy Advisory Committee

April, 1983

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Transmittal of the Report of the Subcommittee on Millimeter- and Submillimeter-Wavelength Astronomy to the Division of Astronomical Sciences, National Science Foundation

The Astronomy Advisory Committee is pleased to transmit to the National Science Foundation the report of its Subcommittee on Millimeter- and Submillimeter-Wavelength Astronomy. This Subcommittee was appointed to assess the future of U.S. mm/submm astronomy, a field which U. S. astronomers have led since its inception, following the failure of the initiative to build a new national mm facility - the 25-meter telescope.

The Subcommittee has reviewed the emerging emphases in the science that need to be addressed by future observations, the adequacy of existing facilities in the U.S. and abroad for making those observations, and the availability of the existing facilities to U. S. astronomers. They have concluded that the existing facilities are both inadequate and insufficient to address the most important issues emerging in this field.

The Advisory Committee endorses the Subcommittee's recommendation that a design study be made for a mm wavelength aperture synthesis array that would provide the angular resolution and sensitivity the science requires, namely, better than 1 arc-second resolution and 1000-2000 square meters of collecting area at a frequency of 115 GHz.

The Advisory Committee recognizes and approves the thrust in the current long-range plans of the Astronomy Division to encourage mm/submm detector development and establish submm wavelength telescopes at superior sites.

The Advisory Committee encourages the Astronomy Division to press for maximum visitor accessibility to existing and future facilities.

Astronomy Advisory Committee
April 29, 1983

PREFACE

In the spring of 1982 it became apparent that the 25-meter mm-wavelength telescope, a project that the National Radio Astronomy Observatory and the mm-wave astronomers had proposed several years ago, would not be funded. At about the same time, the report of the Astronomy Survey Committee, "Astronomy and Astrophysics for the 1980's", was published. This report recognized the importance and contributions of mm-wave astronomy but it assumed that the 25-meter telescope would be built and therefore it made no additional recommendation for millimeter-wavelength facilities. These circumstances left the mm-wave astronomers of the United States without any major new instruments over the next decade. This should be viewed against the background that mm-wave astronomy is an area where the United States has unquestionably led the field and that new instruments are being built by several groups in other countries.

In the fall of 1982 two groups were formed to address this problem, each without the knowledge of the other. At the outset a group of mm-wave astronomers met at Bell Telephone Laboratories (BTL) to discuss the problem of future millimeter- and submillimeter-wavelength facilities. A second group was established by the National Science Foundation (NSF) as a subcommittee of the Astronomy Advisory Committee. This document is the report of that subcommittee.

The NSF and BTL groups have worked closely together over the past eight months. The five members of the NSF subcommittee are also members of the BTL Working Group. The cooperation between the two groups has insured that our report represents a wide sampling of the mm-wave astronomers. Many members of the BTL group contributed to this document, however the responsibility for the report remains that of the subcommittee.

The initial meeting of the BTL Working Group took place in October, 1982, and was attended by eighteen scientists. This meeting discussed both the science and the technology of possible major, new, mmm-wave facilites and concluded that a mm-wave aperture synthesis instrument was feasible and most suited to attack the scientific problems.

The initial meeting of the NSF subcommittee took place in Washington, DC, in December, 1982, and was attended by many members of the BTL Working Group and other members of the mm-wave community who were in Charlottesville for the NRAO Users' Meeting. The Washington meeting primarily focussed on the instruments which were possible at the current, or near future, level of technology.

The second meeting of the subcommitee was a joint meeting of the BTL Working Group, and others, at BTL, Holmdel, New Jersey, in February, 1983. Various members of both groups had written documents detailing the scientific justification of a new major facility and these were discussed in detail. Following this, a consensus was reached as to the nature of the recommendations to be made in this report.

The final meeting of the subcommittee took place in Chicago, April, 1983, at which time a draft of this report was discussed and edited.

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INTRODUCTION

During the last decade the development of millimeter-wavelength and infrared astronomy enabled the first exploration and direct study of the cold universe, a universe rich in astrophysical complexity, activity, and mystery. The dense component of the interstellar gas, typically less than 100 K, can only be observed directly in the mm and infrared portions of the electromagnetic spectrum. Among the results of this new exploration has been a revolution in our understanding of star formation and the early phases of stellar evolution, the discovery of the "Giant Molecular Clouds", the most massive objects in the galaxy, a drastic revision of our knowledge of the physical and chemical conditions of the interstellar medium, and new information on the galactic distribution of the interstellar medium in our galaxy and others.

The impact of this research on the whole of astrophysics is truly significant and only beginning to be fully comprehended. The wealth of new information acquired during the last decade and the promise of important future gains in our astrophysical knowledge compels us to vigorously pursue the continued exploration of the cold universe with new and more powerful observational facilities, both ground-based and in space. As noted in the report of the Astronomy Survey Committee, "Astronomy and Astrophysics for the 1980's", volume 1, page 120, "Because of the importance of such studies to astronomy, the Committee believes it is essential to undertake a greatly expanded program of millimeter-wave astronomy during the coming decade".

At the moment when mm- and sub mm-wavelength studies stand on the threshhold of significant breakthroughs in our understanding of star formation, evolution of normal and active galaxies, the astrophysics of radio galaxies, quasars, and supersonic jets, no new major, national, ground-based observational facilities are being planned or built by the astronomical community in the United States. This is truly an unfortunate circumstance considering that the United States has unquestionably led the technological and scientific development of this area of research. The future of mm-wavelength research in the United States is in doubt. The international community has clearly recognized the vitality and promise of the research. The scientific communities in France, Germany, England, Sweden, Netherlands, and Japan are energetically proceeding with development and implementation of new mm-wavelength facilities. In the light of these developments an assessment of the emerging scientific problems and the future role of mm- and sub mm-wavelength research in American astrophysics is warranted. The report of this subcommittee is an attempt to address these important issues.

CHARGES TO THE SUBCOMMITTEE; SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

In response to the charges the subcommittee was asked to address, the following conclusions and recommendations have been made:

1) <u>What are the emerging emphases in the science to be addressed by observations at millimeter- and submillimeter-wavelengths?</u>

Millimeter- and submillimeter-wavelength observations have been able to make major contributions to astronomy because (1) these wavelengths penetrate the coldest and densest interstellar clouds, and (2) there are many atomic and molecular transitions at these wavelengths which serve as probes of the physical conditions within the clouds. These characteristics are not true for observations at other wavelengths.

Millimeter-wavelength observations have resulted in the discoveries of Giant Molecular Clouds (GMC's), high velocity outflow from young stellar objects, and significant mass loss from red giant stars. In addition, observations have revealed the temperature and velocity distributions in molecular clouds, the chemical complexity of the interstellar medium, and a preliminary look at the molecular gas distribution in nearby galaxies. These results are of vital importance to theories of star formation and one can confidently predict further advances as the sensitivity and angular resolution of mm- and submm-wavelength facilities are improved.

If the results of the past decade can be used as a guide to the next decade, two major areas of research will be the study of star formation and the study of the evolution of galaxies. In particular, since observations of CO trace the distribution of molecular hydrogen, they provide information on the conversion of the interstellar gas into stars and will place constraints on models of the evolution of galaxies. However, at present only the nearest and largest galaxies can be observed due to limited collecting area. Also, the angular resolution of current single-antenna observations is of the order of one arc-minute, vastly inferior to the optical and lower-frequency interferometric radio observations with which the mm-wavelength results are compared. Further progress will be severely limited under these conditions. Sensitivities sufficient to detect GMC's at a distance of the Virgo cluster with angular resolutions of one arc-second at 2.6 mm wavelength, comparable to that achievable at optical wavelengths, are crucial for comparison of optical and microwave observations.

There are other areas of astrophysics where mm- and submm-wavelength observations may be expected to make significant contributions. In cosmology, for example, spatial fluctuations in the microwave background provide information on density fluctuations in the early universe. Also combining any anisotropy in the microwave observations toward a rich cluster with X-ray observations of the same region allow a determination of the distance to the cluster. Studies of radio galaxies, quasars, and BL Lac objects at mm- and submm-wavelengths will close the gap in the spectra between the lower radio frequencies and the infrared where the infrared emission often exceeds the microwave emission by one or two orders of magnitude. Such studies will provide fundamental information on the relative importance of thermal and non-thermal emission mechanisms.

2) Are the millimeter- and submillimeter-wavelength facilities in the United States, at Universities and National Centers, and abroad adequate for the science to be addressed?

The subcommittee concluded that to make major advances in the scientific problems facing mm-wavelength astronomy requires an instrument with an angular resolution of approximately one arc-second, or better, at the $J=1\to0$ transition of CO at 2.6 mm-wavelength, a total collecting area of 1000-2000 square meters, and useable at wavelengths of one mm, and longer. In the United States, the largest single antenna for mm-wavelengths has an area of 150 m^2 and the interferometer with the largest area has 250 m^2. Interferometers can achieve the desired resolution and sensitivity, but those in the U. S. are composed of a small number of elements (three is the current maximum at mm-wavelengths) and therefore require prohibitive amounts of observing time to adequately map a source. This makes them unsuitable for general visitor use by a large segment of the mm-wave astronomers. The subcommittee concluded that the existing instruments in the U. S. for mm-wavelength observations are inadequate for the scientific needs of the community.

Two foreign observatories have major mm-wavelength facilities. The 45-m antenna and the five 10-m antennas of the Nobeyama Radio Observatory, in Japan, have a total collecting area of 2000 m^2 and an angular resolution of 1.5 arc-seconds at the minimum useable wavelength of 2.6 mm. The 30-m antenna of IRAM has a collecting area of 700 m^2, an angular resolution of 21 arc-seconds at $\lambda = 2.6$ mm, and is useable to a wavelength of 1.3 mm. These instruments are not fully operational but it is presumed they will have adequate sensitivity for some of the scientific problems to be attacked. However, neither facility has the proper combination of wavelength coverage, sensitivity, and speed to adequately serve the needs of the astronomical community and to address all the scientific challenges foreseen at mm-wavelengths in the next decade.

There are no facilities in the world designed primarily for submm-wavelength observations. Such observations are done on optical and infrared telescopes as second priority programs. In the United States, the Kuiper Airborne Observatory is equipped with a 0.9-m telescope and the Infrared Telescope Facility on Mauna Kea, Hawaii, has a 3.2-m telescope, with angular resolutions of 96 and 22 arc-seconds, respectively, at $\lambda = 0.35$ mm. The subcommittee concluded that existing facilites are too small to meet the challenges of sub-mm astronomy in the future.

Finally the subcommittee concluded that there are no facilities with an antenna larger than 4-m, at either mm- or submm-wavelengths, in the Southern Hemisphere and this is inadequate.

3) Are the facilities surveyed above accessible to U. S. astronomers? If not, what should be done to improve the accessibility?

In general, university facilites are available on a limited basis, while facilities at the National Centers are readily available to U. S. astronomers. Foreign facilites are in the process of completion and a firm visitor policy remains to be formulated. In any event, foreign facilities will not be, and probably cannot be made to be, sufficiently accessible to adequately serve the needs of the entire U. S. astronomical community. However, the foreign facilities, when completed, will be the best available for mm-wavelength astronomy and one can anticipate U. S. astronomers will be anxious to make use of them.

The subcommittee recommends increased travel support for individual astronomers to improve accessibility to, and make more effective visitor use of, domestic and foreign observatories. The subcommittee further recommends that the IRAM and Nobeyama observatories be added to the NSF list of foreign observatories approved for travel support.

4) What new facilities and instrumentation are required to remedy inadequacies, and what are the relative priorities of implementation?

The subcommittee believes three objectives are essential for the survival of mm- and submm-wavelength astronomy in the United States. The subcommittee recommends these objectives, as its first priority, and further recommends that these objectives be pursued simultaneously. The objectives are:

1) The initiation of a design study of a mm-wavelength aperture synthesis array with a minimum useable wavelength of 1 mm, an angular resolution of 1 arc-second, or better, at a wavelength of 2.6 mm, and a total geometrical collecting area of 1000-2000 square meters. The design study should define the array, the site, and the cost.
2) The construction and the provision of operating support of 10-m class ground-based, submm-wavelength telescopes at relatively dry sites.
3) The provision of support of astronomical research and the development of mm- and submm-wavelength technology relevant to astronomy. This should include increased support of scientists active in mm- and submm-wavelength research, upgrading existing mm-wavelength facilities, and technological developments such as array detectors, submm-wavelength mixers, antenna designs, and correlators.

The subcommittee recommends, as its second priority, the construction of a moderate-size mm-wavelength antenna, typically 10-15-m diameter, in the Southern Hemisphere.

The subcommittee supports the construction of the antennas of the Very Long Baseline Array with sufficient precision that the central portions are useable at a wavelength of 2.6 mm.

The subcommittee endorses observations from space as a means of providing progress in submm-wavelength astronomy.

SCIENTIFIC PROBLEMS RELATED TO OBSERVATIONS AT MILLIMETER-AND SUBMILLIMETER-WAVELENGTHS

The vast majority of mm- and submm-wavelength observations to date have involved the study of the cold interstellar gas. Kinetic temperatures of the gas and dust are typically 10-100 K. Hence the molecules, if observable at all, are in a low state of excitation, radiating almost exclusively at mm- and submm-wavelengths. Molecular hydrogen in dense clouds, the overwhelming constituent, is not directly observable in the low-temperature environment from the ground. Therefore, one is forced to rely on the excitation and observation of molecular lines to trace this vitally important component of the ISM. Centimeter-wavelengths easily penetrate molecular clouds, but spectral lines are few in number and dust emission is negligible. At infrared wavelengths many clouds are optically thick because of the large amounts of dust. These circumstances indicate the importance of mm- and submm-wavelengths for studies of the molecular component of the ISM in our galaxy and others. For example, the most massive objects known in our galaxy, the Giant Molecular Clouds (GMC's), went undetected until the advent of mm-wavelength spectroscopy of the interstellar gas. This emphasizes that no other wavelength range will suffice to observe the cold component of the galactic matter in all its facets.

This section of the report is intended to elaborate on the scientific challenges to which mm- and submm-wavelength observations have made, and will continue to make, contributions or have the potential for future contributions as improvements in technology occur. For reasons of length, the subcommittee chose to emphasize those areas which have been most active, and mention other potential areas of interest more briefly. The discussion should be considered to be representative and not necessarily all-inclusive.

EXTRAGALACTIC AND COSMOLOGICAL STUDIES

On a galactic scale, observations of CO emission in the Milky Way and external galaxies have demonstrated that the distribution of molecular clouds, the cold, dense component of the ISM, is drastically different from that of HI as traced by the 21 cm lines. This has caused a significant revision in our picture of the location and total mass of interstellar matter both in our galaxy and others. Molecular clouds are strongly concentrated in the inner half of the optical disk in many late type external galaxies; in the Milky Way they appear to be concentrated in a ring between 4-8 kpc from the galactic center, and in the galactic center region with a minimum between 1-3 kpc. More specifically, it has been demonstrated that the average CO surface brightness and the average blue surface brightness are strongly correlated across a galactic disk suggesting a linear relationship between the surface density of molecular hydrogen and the stellar surface brightness presumably from stars formed over the past 10^9 years which contribute most to the blue light. While these results are preliminary and limited by the spatial resolution of current instruments, they do for the first time show specific quantitative relationships between the surface density of interstellar matter and starlight; no similar result is apparent from the comprehensive HI data available. Since the evolution of a galactic disk involves primarily the rate and radial dependence of the conversion of the ISM into stars, CO observations are providing astronomers with the first observational constraints on models of galactic evolution.

Spiral galaxies, even galaxies of the same size, differ greatly in their CO luminosity as they do in their optical luminosity; in contrast HI emission intensity and luminosity varies only slightly from one spiral galaxy to another. In addition, the radial distribution of CO emission appears to be related to its morphological type. CO emission thus is much more closely related to the stars as indicated by the optical galactic disk than is HI. This is due to the fact that the molecular clouds being traced by millimeter wave CO emission are the active star forming components of the ISM.

What is missing from the above information on molecular clouds in galaxies is a picture of dark interstellar matter with a resolution comparable to that of optical astronomy. All of the above data have been obtained on single antennas with resolutions of about 45-60 arc-seconds which corresponds to $\sim$ 1-4 kpc for most nearby spiral galaxies at distances between 4-20 Mpc. The much closer spiral M31 is a very weak CO emitter with apparently one order of magnitude less mass in molecular clouds than the Milky Way. In order to understand the relationship of molecular clouds to star formation, galactic evolution and spiral structure we require the equivalent of a photograph of the dark component of galaxies, i.e. high resolution maps of molecular clouds. Only with this development in techniques can the study of the interstellar medium in galaxies make an advance comparable to that which occurred for stellar astronomy when it was realized more than fifty years ago that spiral nebulae were galaxies and the brightest "knots" were entire HII regions.

A resolution of 1 or 2 arc seconds, which will give a picture of individual GMC's and cloud complexes with a resolution of between 20 and 100 pc for galaxies between 4-20 Mpc, is required. This information will provide the missing link in attempts to develop models of galactic evolution. The

Table on page 14 provides a summary of the observational possibilities in the spectral line mode for both galactic and extragalactic objects.

In addition to high spatial resolution, mm-wavelength observations will automatically provide high spectral resolution allowing a kinematic photograph of dark interstellar matter with velocity resolution much higher than obtainable by optical techniques. Measurement of deviations from circular rotation, as well as velocity dispersion of interstellar clouds will provide important data for studies of the dynamics of galaxies. Observation of edge-on spiral galaxies will provide measurements of warps in their disks also important for understanding galactic dynamics.

The very strongest CO emission from our galaxy is from a region which appears to be ringlike about 100-150 parsecs from the center. Many external galaxies also have extremely strong sources located in or near their centers. The most outstanding of these is the Seyfert galaxy NGC 1068; while the strong CO emission may not be correlated with the Seyfert phenomenon, our current observational techniques can only give us a very crude idea of the exact location and nature of the enhancement of emission from molecular clouds near the centers of galaxies. Many of the galaxies with very strong far infrared radiation near their centers also show strong CO emission. Much of this radiation originates from ongoing star formation in molecular clouds. The extraordinary galaxies M82 and NGC 253 are examples of systems where star formation has been turned on at a rate more than an order of magnitude greater than that of normal

OBJECTS POTENTIALLY VISIBLE WITH AN APERTURE SYNTHESIS ARRAY OF ONE ARC SECOND RESOLUTION, 1 MHZ BANDWIDTH, AND 1000 SQUARE METERS COLLECTING AREA

Type of Source	Physical Size	Maximum Distance at which Detectable	Detectable at the Distance of
Small proto-planetary disc	20 AU	20 pc	Nearby stars
Large proto-planetary disc	100 AU	100 pc	Taurus and ρ-Oph clouds
Maser emitting clumps	200 AU	200 pc	Nearest Clouds
Post-shock cooling layer	1000 AU	1 kpc	Gould's Belt clouds
Interstellar disc	0.1 pc	20 kpc	Entire Galaxy
Bipolar flow (molecular jet)	1 pc	200 kpc	Entire Galaxy
Massive molecular cloud core	10 pc	2 Mpc	Local group of galaxies
Forming cluster or association	10 pc	2 Mpc	Local group of galaxies
Giant molecular cloud	100 pc	20 Mpc	Virgo cluster of galaxie
Nuclear disc	400 pc	80 Mpc	Virgo super-cluster
Galactic spiral arm	1 kpc	200 Mpc	Nearby galaxy clusters
Molecule rich galaxy (M82)	10 kpc	2000 Mpc	z=0.2 quasars

bright spiral galaxies. Another example of a very high luminosity CO galaxy is the interesting system referred to as a star burst galaxy NGC 3690-IC 694. This system at a redshift of 3000 km s^{-1} has the highest CO luminosity of any galaxy observed to date. High resolution maps of CO emission in galaxies of this type will provide an understanding of star formation under extreme conditions. Why do these abnormal galaxies have much more active star formation than galaxies with neat spiral arms? Presumably the answer is related to galactic dynamics as well as the total mass of molecular clouds. Observations with a resolution of 1 second of arc will provide a detailed picture of the kinematics of active galaxies and galactic nuclei. Studies of these extreme phenomena may lead to a better understanding of normal star formation.

Over the next decade much new information at infrared wavelengths especially from SIRTF will be obtained on galaxies. It now appears that GMC's are associated with much of the far infrared luminosity. While measurement of the luminosity requires an IR telescope, mm-wavelength observations of high angular resolution are required to reveal the structure and composition of the source of this radiation. In this sense ground-based mm-wavelength observations are complimentary to the new generation of space-based infrared telescopes.

Millimeter-wavelength continuum observations, with high angular resolution and an order-of-magnitude increase in sensitivity, offer the potential for significant advances in cosmology and the study of extragalactic radio sources. With a 1 GHz bandwidth and 1000 m^2 collecting area, a sensitivity of 0.1 mJy is obtainable in several hours at 1 mm wavelength. Many exciting experiments become feasible with such a sensitivity.

The cosmic microwave background radiation is believed to be the remnant radiation of the early universe, now highly redshifted to the microwave region. The temperature of this emission is 3K so that the peak of energy distribution is at $\approx$ 1 mm wavelength. Small-scale angular fluctuations of the microwave background are believed to be characteristic of the density fluctuations in the early universe. These fluctuations are believed to be the origin of clusters of galaxies. Therefore a sensitive study of the anisotropy of the microwave background will provide an important datum for the theories of evolution of the universe.

An extension of these studies offers the potential of determining the scale and evolution of the universe, independent of other methods. As pointed out by Sunyaev and Zeldovich, the hot gas in a rich cluster scatters the 3K background radiation and causes a diminution of the background emission in the direction of the cluster. Detection of this effect, when combined with X-ray observations of the same cluster, allow the determination of the distance to the galactic cluster. Combining the distance with an observed redshift for the cluster would yield values for the Hubble constant and the expansion parameter q_o.

A major question of extragalactic radio sources is the nature of the energy source in the nuclei of these sources. Particle acceleration in extended radio galaxies can be studied from high-frequency mapping. The spectra and polarization of the central components of radio galaxies also provides us with one important clue to the origin of the activity in galactic nuclei. An order-of-magnitude increase in sensitivity is necessary to extend the study of these to problems into the millimeter region. Mapping of the compact cores of quasars and radio galaxies using VLBI is just beginning at mm-wavelengths,but the observations are sorely limited by lack of sensitivity.

Another unsolved extragalactic problem is the lack of radio emission from most quasars. Clearly the emission process, which has a similar optical and infrared spectral shape for both radio loud and radio quiet quasars, must turn over at some frequency in the far infrared or millimeter wave. Much greater sensitivity in the millimeter region should allow significant progress on this problem.

GALACTIC STUDIES

The advances in our knowledge of the galaxy derived from mm- and submm-wavelength observations have been almost exclusively in our knowledge of the interstellar medium, its physical and dynamical state, its chemical composition, and its relation to star formation. These three areas are inseparable. For this reason it is impossible to discuss one area to the exclusion of the others and no attempt is made to do so here.

The power of mm-wavelength astronomy for studying the cold component of the universe lies in the exceptionally large variety of spectral lines observable in this portion of the spectrum. Spectral lines of over 50 molecular species, including isotopic substitutions, provide astronomers with a rich variety of tools with which to probe the physics and chemistry of interstellar clouds and regions of star formation. Some species can be used to probe the fractional ionization of the gas; still others can be used to study its isotopic composition. By choosing the right spectral lines to observe, virtually any set of physical parameters can be investigated. Combined with the coherent detection capabilities inherent to radio instrumentation, the richness of the electromagnetic spectrum near 1 millimeter-wavelength, makes this window one of the most rewarding spectral regions to explore in the immediate future. It is in this window where we can study the interstellar material which fuels the formation of stars and planets, maybe the activity in active galaxies, and perhaps provides the chemical foundation of life itself.

The interstellar medium is one of the most active components of a galaxy. Its contents are repeatedly recycled through successive generations of massive stars. As gravitational collapse converts the interstellar medium into stars, the mass loss from dying red giants and supernovae replenishes the interstellar medium with gas enriched in its elemental composition by thermonuclear processing. Star formation may be the single most significant process controlling this cycle. The fraction of mass going into the formation of high mass stars determines the longevity of the interstellar medium in the absence of external forces.

Star formation can control the chemical evolution of our galaxy. Which thermonuclear processes dominate elemental enrichment? By studying the isotopic composition of molecular clouds in our galaxy, and others, and their abundance gradients, we may be able to untangle the web of intricate processes which control the evolution of galaxies.

Stars form from molecular clouds. Therefore, detailed understanding of the actual physical process of star birth requires an understanding of the process of collapse and fragmentation of molecular clouds. We need to know the velocity, density, and temperature structure of molecular clouds over size scales ranging between 1 AU and a few parsecs. This requires observation of many molecular lines and with considerably higher angular resolution than now possible. To date most millimeter-wave observations have been made with telescopes having resolving powers around one arc-minute. Instruments with resolving powers one to two orders of magnitude better are needed.

It is in this important area that mm-wavelengths have unique capabilities. At cm wavelengths, the VLA has the necessary one arc-second resolution. However, the emission of the dust in protostellar regions is too faint at centimeter wavelengths. Furthermore, the spectral lines are too few in number and intrinsically weak at the longer wavelengths for them to be very useful probes of interstellar regions. Because of the Planck function and the generally greater strengths of lines in the far-infrared, this part of the spectrum would be ideal were it not for the relatively poor angular resolution of the telescopes that can be flown above the atmospheric water vapor. Note also that although ground-based telescopes do have the resolution to study warm protostars in the accessible infra-red, many of these regions are optically thick even at wavelengths as long as 30 μm and hidden from view. Thus the mm-wavelength spectral region must be the choice for many aspects of star formation studies, but major improvements in sensitivity and angular resolution are needed to make significant advances in our knowledge of star formation.

The past decade has witnessed a revolution in our understanding of the chemical complexity of the interstellar medium, largely as a result of radio observations of mm-wavelength emission from molecules. Interstellar clouds and late-type stars are now known to be prodigious producers of molecules. The problem of how such molecules are formed has been a central question since their discovery. The temperature,density environment in the clouds is vastly different from those usually encountered in the laboratory, and so studies of the cloud chemistry can provide important information about our understanding of chemical reactions. Indeed, many suggestions originally made to explain molecular abundances in clouds stimulated laboratory researchers to develop new methods of measurement for gas phase reactions.

A major contribution to our understanding of the interstellar chemistry was the suggestion that ion molecule reactions initiate molecule production. Reactions such as $C^+ + H_2 \rightarrow CH_2^+$ + photon, or $H_3^+ + O \rightarrow OH^+ + H_2$, can proceed rapidly at the low temperatures present in the clouds and thus produce molecules more rapidly than neutral species reactions. In the ion-molecule chemistry the reacting ions can be produced by cosmic rays or UV radiation, and generally require that the gas be primarily molecular hydrogen. In the deep interiors of clouds for example, cosmic ray ionization of H_2 produces H_2^+, which then reacts to form H_3^+. It is this molecular ion which drives the chemistry since it can transfer protons to some atomic species, as illustrated above.

Observational confirmation of the ion-molecule model of chemistry in dense clouds has been excellent. It correctly predicts the presence of molecular ions, such as HCO^+, N_2H^+, and HCS^+, the large enhancement of deuterated molecules DCN, DCO^+, N_2D^+ compared to the hydrogen form, and the presence of isomeric forms HNC and HCN. The ion molecule chemistry is most successful in predicting the abundances of simple molecules but, for structures more complicated than formaldehyde, problems remain. These complicated species may be produced by other mechanisms which are not pervasive throughout a cloud, such as in the protostellar nebula. Around evolved stars, in shocked molecular gas, and where UV radiation is present, chemical abundances change significantly over small distances. Observations with high angular resolution are needed to test the detailed models of the chemistry of these regions.

Variations of molecular abundances due to photochemistry also occur in molecular clouds near their edges and near embedded sources, such as newly formed hot stars. Model calculations of ion-molecule chemistry including photodestruction show that molecular abundances vary by an order of magnitude over small distances as the UV radiation is absorbed by grains and molecular lines. For example, C_2H, whose millimeter spectrum was first identified in interstellar clouds, is predicted to have a peak abundance near the edge, about 1 - 2 magnitudes of visual extinction inwards. At a hydrogen density of 10^3 cm^{-3} this peaking occurs within 1' to 2' for a source at $\sim$ 500 pc. Other examples are OH and H_2O which increase dramatically within a fraction of a magnitude of extinction according to model calculations. A final example is CO which should have a sharp transition in abundance due to self-shielding.

To date very few studies have been done to test the photochemistry in molecular clouds. Maps of CO at the edge have been made at 1' spacing for the relatively nearby cloud B5, and large variations in CO abundance were recorded over 2', indicating a sharp edge, but were still not fine enough to reveal the structure of the transition.

The chemistry of shocked interstellar gas is another subject which would benefit from high resolution observations. Shocks are widespread and prevalent in the interstellar medium. They occur during the birth and death of stars, near HII regions, and from collisions between clouds. The evolution of a shock depends on the molecular composition and in turn the shocks change the chemical composition. Observations of millimeter and submillimeter lines of molecules provide a unique probe with which to determine the properties of shocks.

At present there is little detailed information about shock profiles as no observations exist of the abundance profiles. Theoretical calculations show vastly different abundance profiles for different shock conditions. To test models of shock propagation, chemistry, and cooling it is necessary to observe molecular emission with high spatial resolution. Significant variations in chemical abundances occur over a small spatial scale, as small as $\sim 5 \times 10^{15}$ cm. At the distance of Orion, $\sim$ 500 pc, a resolution of $\sim$ 0.5 arcseconds is needed to study its structure. The importance of shocks and shock chemistry in interstellar clouds cannot be overestimated. They transfer energy to the gas, initiate star formation, and change the molecular composition. An understanding of shock chemistry and structure is important and requires increased sensitivity and better angular resolution.

The detection and subsequent study of interstellar molecular gas has enabled us to obtain the first detailed glimpses into the physical processes occurring in stellar birth and early evolution. As a result of a synthesis of molecular line observations with infrared, optical and radio frequency data, a coherent picture of these astrophysically important processes is beginning to emerge. This new picture unites a number of seemingly unrelated astronomical phenomena known from optical, infrared, radio and mm-wavelength studies.

Star formation occurs when portions of a molecular cloud become gravitationally unstable, fragment, and collapse. Usually, stars form in groups. The most massive members heat the surrounding gas and dust, appearing as bright infrared sources embedded in localized regions of enhanced gas temperature within the molecular cloud. As stars evolve toward the main sequence they produce energetic winds which shock and accelerate the surrounding molecular gas. The manifestations of this wind-cloud interaction are observed across a broad range of the electromagnetic spectrum: as extended supersonic flows of cold molecular gas, at mm-wavelengths; and near the surface of a molecular cloud, as optically visible, shocked high velocity ionized gas flows, otherwise known as Herbig-Haro objects. The more massive stars in a newly formed group evolve very rapidly toward the main sequence, and produce copious amounts of ultraviolet radiation. This radiation dissociates and ionizes surrounding molecular gas, creating hot high pressure HII regions. These HII regions expand and first appear as compact regions of cm-wavelength continuum emission embedded within the molecular cloud. Eventually they increase in size until they burst out of the cloud, transforming large amounts of the surrounding molecular gas into a bright visible nebula of hot ionized gas. As the visible nebulae evolve, more of the molecular gas is destroyed, ionized and dissipated into interstellar space; the once embedded group of young stars is liberated from the molecular cloud appearing as an optically visible cluster or OB association.

The most massive members of the group may self-destruct in a supernova explosion further disrupting and eroding the original molecular cloud. Typically only a small fraction of the original cloud is processed into stars, the rest is evaporated into interstellar space or pushed great distances from the stars to be recollected again for a subsequent episode of star formation. Armed with this global view of star formation and with detailed information about the temperatures, densities and energetics of molecular gas and dust directly provided by mm-wavelength and infrared observations, the beginnings of a theoretical foundation for understanding the star formation process is being developed, tested and refined.

The opening of the cold universe to exploration by mm-wavelength and infrared observation has enabled significant progress to be made toward our understanding of star formation. However, we have only taken the first small steps toward the solution of this astrophysically important and intriguing problem. Desire to pursue this problem to its ultimate solution compels us to make every effort possible to insure a continued and vigorous exploration of the cold component of the universe. And this can only be accomplished through continual development of and improvement in mm-, and submm-, and infrared-wavelength observational capabilities.

One of the most recent and exciting discoveries made by mm-wavelength CO observations is the detection of massive and energetic molecular outflows around very young stars. The existence of such energetic outflows of cold material was totally unexpected and the high frequency of occurrence of the phenomenon suggests a total revision of our understanding of early stellar evolution. The rate of formation of such outflows is comparable to the star formation rate, and the mechanical luminosity in these molecular winds is estimated to be as much as 1-10 percent of the radiant luminosity of the star driving the outflow. Particularly intriguing and surprising was the finding that most outflows appear bipolar in nature. Indeed, some are very well collimated into a pair of oppositely directed jets. Those cold gas jets are morphologically similar to the structure of extragalactic radio sources, suggesting that jet formation is a property of astrophysical systems with vastly different physical parameters. We have a great deal to learn about astrophysical fluid dynamics.

The discovery of bipolar molecular mass outflow in star formation regions may tie together several apparently unrelated phenomena as manifestations of the same underlying physical process. Powerful maser emission from water vapor is seen in most molecular outflow sources. Near-infrared lines of H_2 and optical emission lines of H, S, N, and O in Herbig-Haro objects are formed in radiative shocks where a stellar wind interacts with ambient cloud material. Both maser and Herbig-haro objects show large proper motions away from highly obscured young stars. Observations of these sources may provide us with an ideal laboratory for studying the physics and chemistry of interstellar shock waves.

Other interesting galactic projects related to stellar evolution can also be carried out with improved observational capability at mm-wavelengths. Among them are detection of small HII regions which still have optically thick thermal spectra. These objects indicate high densities and thus are likely to be regions undergoing star formation. In later stages of evolution the dust emission in proto-stellar/planetary systems can actually be mapped at 0.1 to 1.0 arc-second resolution. Supernova remnants also present some of the same problems with particle acceleration as the lobes of radio galaxies and thus are interesting to map at the highest frequencies. The great advantage is that they are close,permitting much higher spatial resolution. Stellar observations are also possible due to the resolution and sensitivity of an array. The photospheres and chromospheres of many stars should be detectable. Recent VLA observations in the centimeter bands suggest that many cool stars have more extended atmospheres than previously thought. Large numbers of giants and supergiants have detectable emission. Thus studies of the photospheres/chromospheres of these and other anomolously excited stars at very high resolution should be possible for the first time.

Mapping of hot stellar wind objects and proto-planetary nebulae with the VLA are providing structural and other physical information. However, with improved resolution at mm-wavelengths hundreds of such objects can be mapped at frequencies where they are optically thin so that true density profiles will be easily obtained. Both pre-PN red supergiant winds and the so called "superwinds" causing PN shell ejection can be studied. This mass loss is a critical parameter in the modelling of stellar evolution of such systems and is probably unknown by orders of magnitude. Thus mm-wavelength observations at 1 arc-second resolution offer promise of a much clearer understanding of the stellar evolution of stars in the upper part of the HR diagram.

About 20% of the mass within the core of our galaxy is in molecular form. The star formation rate, inferred from the thermal continuum radiation produced in the inner 100 pcs of the galaxy, is about 2 orders of magnitude greater than in the solar vicinity. The largest known molecular cloud complex in the galaxy, Sgr B2, lies within 100 pc of the dynamical center. The large velocity gradients, and high densities of both old stars and gas implies that star formation occurs under different conditions than in the galactic disc. Is the mass spectrum of newly formed stars in the galactic center different from other regions of the galaxy? Are processes such as self-propagating star formation affected? Can clusters and associations still form? In order to study individual star forming regions within the galactic core arc-second resolution instrumentation is required.

The molecular gas is potentially the best tracer of the dynamics and kinematics of the inner few parsecs of the core. The clouds can be used to trace the mass distribution and density profile of this region. The same phemomena are present in central regions of more distant galaxies but cannot be resolved. The presently available arc-minute diameter mm-wavelength telescope beams are too large to probe the innermost parsec; the velocity gradients smear the spectral lines over many 10's of kilometers per-second.

However, an instrument with arc-second resolution could study the dynamics down to a few-hundreths of a pc. Dynamical information on this scale may tell us whether or not there is a supermassive collapsed object at the dynamical center of the galaxy. Detailed, high sensitivity mapping of this region can also be used to dynamically probe orbits followed by ballistic particles and map the gravitational potential. Such a study could establish the presence or absence of a bar in the inner regions of the galaxy. Study of our own galactic center gives us a unique opportunity to study a galactic nucleus at close range. We may gain many insights which will help us understand activity in other galactic nuclei.

SOLAR SYSTEM STUDIES

The Planets - All the planets will be objects of research as increased sensitivity becomes available at mm- and submm-wavelengths and, in many cases, the studies may be considered as a wavelength extension of the VLA. For example, at VLA frequencies the planetary atmospheres are probed to the 10-100 bar level whereas mm-wavelengths will probe from 0.1 to several bars. This capability may be particularly important for the investigation of the belt and zone structure on Jupiter. It is believed that this structure is related to relative rising and sinking of atmospheric gases, ammonia in particular which is probably the major opacity source in the atmospheres of Jupiter and Saturn in the wavelength range from 1 mm to 10 cm. Millimeter-wavelength observations are required to properly measure relative limb darkening in belts and zones and bulk structural variations toward the poles with 1 arc-second, or better, resolution.

The structure and chemistry of Saturn's Rings remains a major question in planetology in spite of the enormous success of the Voyager mission. Most of the Voyager measurements involve the extreme small end of the particle size distribution in the various Rings since visual and IR techniques were used. Earth-based observations have shown that the full size distributions are such that the (ice) particles remain essentially transparent at wavelengths longer than a cm, but exhibit true thermal emission at $\lambda \leq 3$ mm. Thus, the wavelength range of 1-3 mm is ideal to investigate the bulk of the mass of the Rings.

Microwave spectroscopy in the planetary systems has not as yet proved to be important except for CO lines in the atmospheres of Venus and Mars. The first two rotational transitions of CO allow sensitive probing in the 'mesospheres' of these two planets in unique ways. On Venus the atmosphere just above the clouds, i.e. 60 km to 125 km, can be investigated for temperature structure and CO altitude mixing profiles as a function of solar phase angle. It is quite clear that CO is created on the day side of the planet by photodissociation of CO_2 and that the CO rapidly flows from the subsolar to the antisolar points reaching supersonic flow at the terminator. Clearly, the accurate mapping of

CO in three dimensions, particularly near the morning and evening terminators, will create a powerful data set for the investigation of the general circulation on that planet.

Major Satellites and Asteroids - The major satellites of Jupiter: Io, Europa, Ganymede and Callisto as well as Saturn's Titan are all of scientific interest, equal to that of the planets. Their disks could be partially resolved at mm-, wavelengths. All of the satellites rotate synchronously with their orbit and, consequently, exhibit all longitudes to the Earth in an orbital period. Variations in emission temperatures during a rotation would be caused by variations in albedo and, possibly, heat flow from the interior, e.g., especially Io. Titan is a very unique satellite since it has an atmosphere more massive than Earth's. Theories strongly suggest that microwave spectral lines of CO should be present in Titan and sulfur compounds, such as SO_2 and SO in Io.

The five major asteroids are similar in angular size at close passages to the major satellites and also could be partially spatially resolved at mm-wavelengths. At least 15 other asteroids exceed 0.2 arc-seconds. The important questions concerning asteroids which would be answered with systematic observations in the mm-, cm-, and infrared-wavelength ranges include radii, albedos, masses and possibly heat flow from radioactive materials.

Comets - Following the success of radio observations of Comet Kohoutek

(1973 XII), it was believed that radio searches for complex cometary molecular species had a bright future. Unfortunately, this has not been true. While the OH molecule has been observed in at least 11 comets, the only other molecules observed by radio astronomers are HCN, CH_3CN, and CH, all from Comet Kohoutek (1973 XII), and possibly H_2O from Comet Bradfield (1974 III). These sparse results are not due to a lack of effort because hundreds of telescope hours have been used in searching at least 6 other comets for complex molecular species with no success.

Future progress will have to come from radio interferometric observations. Recently, the potential of interferometric observations of comets was nicely demonstrated by VLA observations of Comet Austin (1982g), which showed that the icy grain halo model fails to predict the continuum flux; therefore, the so-called icy composition of comets is not as well understood as was believed previously. In the future, both millimeter continuum and line observations will be required to determine the composition of the nucleus and coma of comets. With high spatial resolution, double-peaked velocity profiles, corresponding to the forward and backward gas streams, should be observable. Careful nuclear mapping is expected to resolve the various discrepancies which have developed between the radio, optical, and ultraviolet observations. We expect that careful observational confirmation of cometary maser pumping model predictions will be applicable to furthering our understanding of the still rather enigmatic galactic masers.

<u>The Sun</u> - Millimeter-wavelength emissions of the Sun originate from the chromospheric levels, and therefore studies at mm-wavelengths should give us information on the solar chromospheric parameters, its structure, density and temperature up to heights of approximately 5000 km. Present measurements of the quiet sun brightness distribution with resolution of the order of 1 arc-minute provide information on the spicules and interspicular regions in the lower chromosphere. This is particularly important at heights below $\sim$ 2000 km, since optical observations cannot provide such information. It is important to investigate if the brightness distribution is uniform, limb-darkened or limb-brightened as a function of wavelength across the millimeter band because such distributions are affected by spicules. With resolution of approximately 1 arc-second it may also be possible to observe the individual spicules at the limb and estimate more directly their physical parameters such as their temperature and density.

With high angular resolution one may be able to determine the magnetic field topology of the flaring region before the energy is released impulsively. Since flare models are based upon theoretical magnetic field configurations, and since flare energy release is believed to take place in the chromospheric levels, one is likely to make fundamental contributions to the process of energy release in solar flares. In particular, one should be able to answer the following questions: does the energy release take place by tearing mode instability in a single flaring loop or in an arcade of loops, or is the creation of a current sheet by two juxtaposed bipolar loops with opposing polarities an essential requirement for the impulsive onset of a flare.

Observations of solar bursts in the mm-wavelength range will provide an important diagnostic of the second stage electron acceleration process. Such bursts at frequencies greater than 25 GHz are produced by electrons in the Mev range, which also produce gamma ray bursts. Gamma ray lines are also observed, produced by energetic protons. Simultaneous observations of millimeter and gamma ray bursts from ground based and space observatories should provide important clues to the electron and proton acceleration processes.

Since prominences at millimeter wavelengths are observed on the disk as absorption and at the limb as emission phenomena, with high angular resolution, the order of 1 arc-second, one should be able to resolve the filamentary cavities and other fine structures in filaments. Such structures have an important bearing on the physics of formation of prominences, and their physical parameters such as density, temperature and the filament sheath surrounding the core and the magnetic fields.

ADEQUACY OF EXISTING FACILITIES

The subcommittee concluded that to meet the needs of the astronomical community of the United States in the next decade a national mm-wavelength facility, open to all qualified scientists on a competitive basis, was required. The scientific problems to be addressed dictate an angular resolution of 1 arc-second at the $J = 1 \rightarrow 0$ transition of CO at 2.6 mm wavelength, a total collecting area of 1000–2000 square meters, useable at wavelengths of 1 mm, and longer, and of sufficient speed to serve a significant fraction of the astronomical community.

The Tables on pages 36 and 37 summarize the collecting areas and angular resolutions, at 2.6 mm wavelength, of the major single antennas and interferometers capable of operation at mm-wavelengths. With a single antenna, the resolutions range from 15 to 90 arc-seconds, comparable to the resolution of the unaided human eye. This is grossly inadequate for the study of the mass distribution in external galaxies, for example. To provide a comparison with optical photographs a resolution of 1 arc-second is required. Since to obtain this resolution with a single antenna would require a diameter of 650 m, clearly prohibitive with current technology, the use of mm-wavelength interferometers is mandatory.

The ability to do mm-wavelength interferometry has been demonstrated at the University of California, Berkeley, and at California Institute of Technology, with three-element interferometers, and by obtaining fringes in

MAJOR SINGLE MILLIMETER-WAVELENGTH ANTENNAS

Observatory	Diameter(m)	Geometrical Area (m^2)	Beamwidth (arc-sec) (λ = 2.6mm)
Bell Telephone Lab.	7	38	92
NRAO, Kitt Peak	12	113	54
FCRAO, Amherst, MA	13.7	147	47
SRC, Mauna Kea *	15	177	43
Onsala, Sweden	20	314	32
IRAM, Spain **	30	707	21
Nobeyama, Japan	45	1600	15

* Under construction. Expected to be operational in 1985.

** Expected to be operational in 1984.

MILLIMETER-WAVELENGTH INTERFEROMETERS

Observatory	Number of Elements	Total Area (m^2)	Maximum Baseline (m)	Resolution (arc-sec at λ = 2.6 mm)
U-C, Berkeley	3	85	300(E-W), 200(N-S)	1.5
CIT, Owens Valley	3	255	150(E-W), 100(N-S)	3
IRAM, France *	3	530	320(E-W), 200(N-S)	1.5
Nobeyama, Japan	5	395	560(E-W), 520(N-S)	0.8

*Under construction. Expected to be operational in 1987.

SUBMILLIMETER-WAVELENGTH ANTENNAS

Location	Diameter (m)	Geometrical Area (m^2)	Beamwidth (arc-sec) (λ = 0.35mm)
KAO	0.9	0.64	96
IRTF, Mauna Kea	3.2	8	22
Arizona/MPI*	10	79	9
Cal Tech**	10.4	85	8

* Under construction. Expected to be operational in 1985.

**Proposal pending at the NSF. Proposed to be operational in 1985.

a VLBI experiment using baselines of 2000 km. Comparable mm-wavelength interferometers are under construction at the present time overseas. These are the five-element aperture synthesis interferometer at the Nobeyama Radio Observatory, in Japan, and a three-element interferometer of IRAM on the Plateau de Bure in France. While all the above interferometers will have a resolution of 1-3 arc-seconds at 2.6 mm wavelength, the interferometers are composed of a small number of elements, either 3 or 5. The implications of this are that they are capable of sampling a limited portion of the u-v plane and thus provide only a limited number of components of the Fourier transform of the brightness distribution of the source. To obtain a more complete brightness distribution the antennas must be moved to other positions to obtain additional Fourier components and thereby synthesize a more completely filled aperture. This greatly increases the observing time to map a source, places prohibitive requirements on observing time, and makes them unsuitable for general visitor use.

The subcommittee concluded that the existing facilities in the United States are inadequate in terms of collecting area and speed to serve the needs of the astronomers over the next decade. The foreign facilities under construction will provide an improvement but they too will be lacking in one respect or another from what the subcommittee believes will be needed. For example, both facilities will lack speed because of the small number of elements. In addition, Nobeyama is not expected to operate at wavelengths less than 2.6 mm.

At submm-wavelengths the status of the facilities is somewhat brighter. Two ground-based, single-antenna instruments are planned or under construction in the United States. The University of Arizona and the Max-Planck-Institut für Radioastronomie, Bonn, are jointly constructing a 10-m telescope in Arizona, and Cal Tech has proposed to the NSF the construction of a 10.4-m telescope on Mauna Kea in Hawaii. These telescopes are expected to operate at $\lambda \geq 0.35$ mm with an angular resolution of 8 arc-seconds.

The Arizona/MPI and Cal Tech instruments are an important and vital step toward continuing progress in submm-wavelength astronomy. The Cal Tech instrument, if funded, is expected to be available to visiting astronomers approximately one half of the time. Because submm-wavelength research and technology are not as advanced as at mm-wavelengths, the subcommittee believes these, or similar, ground-based instruments are adequate for the near future.

The subcommittee calls attention to a gross inadequacy in the overall picture of mm-wavelength astronomy - the lack of observing facilities, larger than the 4-m diameter, in the Southern Hemisphere. This leaves a large portion of the galactic plane which cannot be surveyed at mm-wavelengths since it is not visible from observatories at northern latitudes. Also, the nearest galaxies are available only from southern observatories. Finally, for correlation of mm-wavelength observations with infrared observations from spacecraft, such as the Shuttle Infrared Telescope Facility, a telescope in the Southern Hemisphere is required.

A cooperative effort involving IRAM, Onsala, and ESO is underway with a goal of establishing a 15-m telescope, useable at mm- and perhaps submm-wavelengths, in the Southern Hemisphere. If project approval and funding is received, construction might begin in 1985. Such an instrument would provide a significant increase in mm-wavelength observing capability in the Southern Hemisphere.

ACCESSIBILITY OF EXISTING FACILITIES

All the mm-wavelength facilities in the United States are available in varying degrees for use by visiting scientists and graduate students. The 12-m telescope of the NRAO at Kitt Peak is available to any scientist on a competitive basis, i.e. after a review and merit rating of the observing proposal by referees. The facility is well staffed by NRAO, and their administrative and operational policies are specifically geared to visitor use. In addition travel for two people per observing run is partially subsidized.

University-operated mm-wavelength facilities are available also for visitor use but on a less formal basis. Usually a visitor is expected to operate the telescope and receivers, after a period of indoctrination, and data reduction facilities may be less extensive than at the National centers.

The "hands on" experience provided by this mode of operation is valuable, but can also be expensive because a mimimum of two people is required for around-the-clock observing and there is no travel subsidy.

The primary foreign mm-wavelength facilities which will be of interest to U.S. astronomers are those of Nobeyama and IRAM. Both facilities are nearing completion, not now open to visitors, but were contacted in an attempt to ascertain future visitor policies. In both cases visitor use is expected, initially on a collaborative basis with a resident scientist. It is anticipated, by both observatories, as operating experience is gained by the observatory staff, that eventually visitors may use the instruments without collaboration. Neither observatory was prepared, at this time, to stipulate what fraction of the observing time might be available for visitors.

The foreign facilities, when completed, will be the best mm-wavelength instruments in the world and, as such, U. S. astronomers will undoubtedly submit proposals for observing time. However, these facilities will not be available a sufficient amount of time to meet the needs of the entire U. S. community of users and will not be a substitute for a major, national instrument in the United States. Also, the foreign facilities will not have the combination of collecting area, angular resolution, minimum useable wavelength, and speed which the subcommittee believes is required for the scientific problems of the next decade.

It is well recognized that a major deterrent to using domestic or foreign facilities of another institution is the travel costs involved, which usually must be taken from the budget of the individual astronomer. The NSF is to be commended for its program of travel support for the use of major instruments overseas, a program administered through NRAO and KPNO and includes the major radio, optical, and infrared telescopes of the world. This program will become of prime importance to mm-wavelength observers as the foreign facilities become superior to those in the U. S. The subcommittee recommends that the NSF add the IRAM and Nobeyama observatories to the list of foreign instruments approved for travel support.

It should be recognized that even a vigorous and heavily-subscribed foreign travel support program is hardly an acceptable substitute for a major, national, mm-wavelength instrument in the U. S. The NSF program stipulates that the reimbursement for the use of major instruments overseas applies to one investigator for each observing program. This is a severe restriction when it is viewed in the context of training graduate students. Inevitably one wants at least one graduate student and the principal investigator to use an instrument at any one time. Also these instruments are available perhaps once a year, at best, and this is also incompatible with the training of graduate students.

To improve the ability to use domestic and foreign facilities the subcommittee recommends increased travel support to scientists and their graduate students through the scientists' research grants.

RECOMMENDED FACILITIES AND INSTRUMENTATION

In view of the scientific problems which can be addressed by observations at mm- and submm-wavelengths in the next decade, and beyond, and in view of the lack of any new, major, mm-wavelength facility in the United States with which to address these problems, the first priority recommendation of the subcommittee is to pursue simultaneously three parallel objectives directed toward (1) ultimately providing a major, national, mm-wavelength facility, (2) providing improved submm-wavelength observing facilities, and (3) providing support for current research groups, upgrading current operating facilities, and research and development of mm- and submm-wavelength technology. The subcommittee is unable to prioritize these three objectives. Objectives (1) and (2) apply to different wavelength domains and (3) is of overriding importance to the maintenance of a viable mm- and submm-wavelength research effort in the United States. Furthermore, all three objectives can, and should, be carried out concurrently.

The subcommittee believes that the scientific needs of the astronomical community require a new, national facility for mm-wavelength observations. The capabilities of this facility should be such as to provide 1 arc-second angular resolution, or better, at 2.6 mm-wavelength, operate efficiently at a wavelength of 1 mm, and longer, and have a total collecting area of 1000 - 2000 square meters. It is the opinion of the subcommittee that such a facility is feasible with current technology and would be at the forefront of scientific research for at least two decades. Recent advances in mm-wavelength technology and our knowledge of the phase effect of the terrestrial atmosphere at these wavelengths make this a feasible and exciting project to undertake at the present time.

The initial step toward the realization of this instrument should be a design study to define the array in terms of the number of antennas, their individual size or sizes, the configuration, correlator design, the software required, possible observatory sites, etc. The end result of such a study should be detailed specifications of the final array. A project of this magnitude would be a national facility. It may well be that such an instrument would be situated with the present VLA in New Mexico in order to take advantage of the great expertise of the VLA staff, and to control costs without making a major sacrifice in scientific capability.

The question can be raised why the mm-wavelength astronomers prefer an array instead of a large, single antenna. This is a valid question and deserves an answer. When the 25-meter telescope was originally designed and proposed, in early- to mid-1970's, the concept of a large telescope, sited on Mauna Kea, operable to $\lambda \geq 0.7$ mm, was an exciting possibility and would have been the leading mm-wavelength instrument in the world. As the funding of this telescope was delayed from year to year its potential dominance decreased, the science advanced, technological progress led to increasingly sensitive and reliable receivers, and the feasibility of interferometry at mm-wavelengths was demonstrated. The last two factors were most vital. Many mm-wavelength astronomers, including the majority of the subcommittee, still feel a large, fully-steerable telescope would be a valuable instrument, but it would no longer provide a "quantum jump" to the scientific field. The subcommittee believes that the proposed mm-wavelength array will provide major advances in the science, that it will be the leading instrument in the world for more than a decade, and that it is technically possible in the mid-1980's.

The subcommittee recommends the construction and support of ground-based facilities dedicated to submm-wavelength observations. Such facilities are totally lacking in the world at the current time. At present, submm-wavelength observations are carried out on small telescopes devoted primarily to infrared astronomy. Advances in the fabrication of precise antenna surfaces and in submm-wavelength receiver technology make the exploration of the submm-wavelength region particularly attractive and feasible. This is an area of research recognized and encouraged by the Astronomy Survey Committee as they gave their highest priority, among small new programs, to the construction of a 10-m class telescope at an excellent ground-based site.

A prerequisite to the maintenance and growth of an active research program in the United States in mm- and submm-wavelength astronomy is providing adequate funding of current research programs, upgrading existing facilities, and supporting research and development of mm- and submm-wavelength devices and techniques. Recognizing that no new, major, national mm-wavelength facility could be operational until the late 1980's, at the earliest, the subcommittee recommends increased support of these areas. The U. S. astronomical community has lost its lead in mm-wavelength facilities and will do so in scientific output and technological development without increased support in these areas. The existing mm-wavelength interferometers at U-C Berkeley and Cal Tech represent the best angular resolution available, at 2.6 mm wavelength, in the U.S. and upgrading these facilities will provide vital impetus to the national research effort in the 1980's. Furthermore, support of university groups, with and without their own facilities, is imperative to maintaining a viable national effort at mm- and submm-wavelengths.

The sensitivity of mm-wavelength receivers has improved markedly over the last decade but still falls short of the theoretical quantum limit by an order of magnitude, or more. Continued progress in this area is extremely important and can be anticipated if development programs are funded. Also, present and future mm-wavelength antennas may be more efficiently utilized if waveguide feeds could be developed to provide multiple beams with a single antenna. This may be accomplished by having an array of feeds and detectors in the focal plane of the telescope but current technology has not achieved this. The subcommittee supports the funding of the development of array detectors at mm-wavelengths to provide multiple beams in single antennas.

As its second priority, the subcommittee recommends the construction of a medium size, mm-wavelength, telescope, 10-15-meter diameter, in the Southern Hemisphere. Existing facilities, of this size or larger, are totally lacking in the Southern Hemisphere, yet more of the galactic plane is observable from typical latitudes of Southern observatories than in the Northern Hemisphere, and the nearest galaxies are visible from the Southern Hemisphere. A prime use of such a telescope would be for molecular spectroscopy to extend the studies of galactic structure and the distribution of GMC's to the Southern sky.

The subcommittee supports the construction of the antennas of the Very Long Baseline Array with sufficient surface accuracy to allow the use of the central portions of the antennas at 2.6 mm-wavelength. Interferometry at mm-wavelengths has been accomplished on a baseline of 2000 km, and it can be expected exciting results could be obtained by the entire VLBA, providing angular resolutions of $\sim 10^{-4}$ arc-seconds. This unprecedented resolution would set the stage for studies of the central regions of active galaxies, the cores of quasars, and the nucleus of our galaxy with a spatial resolution of the order of 1 A.U.

The subcommittee endorses the concept of submm-wavelength observatories in space. Ground-based observations in this wavelength region are limited to $\lambda \geq 0.35$ mm because of absorption in the terrestrial atmosphere. A reflector in space would free astronomers of this limitation and extend submm-wavelength observations to overlap with the far-infrared.