MILLIMETER ARRAY
MEMO NO. 2

SCIENCE WITH A MILLIMETER ARRAY

VARIOUS AUTHORS

These documents were submitted to the NSF committee on the future of millimeter astronomy (Bell Labs, Feb. 10-11, 1983). They represent fairly, but not totally, complete summary of the science one might do with a millimeter array.

CONTINUUM WORK WITH A MILLIMETER ARRAY

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I. Cosmology

A. Microwave decrement in clusters => q_o, H_o with AXAF x-ray data.

B. Anisotropy in 3K background

C. High z protogalaxies?

II. Extragalactic

A. Mapping of extended emission in radio galaxies at millimeter wavelengths => particle acceleration mechanisms.

B. Spectra of central components in radio galaxies

C. Radio quiet quasar detections, spectra

D. Separation of thermal - non thermal emission in normal galaxies

III. Galactic/Star Formation

A. Detection of High Density HII regions (star formation)

B. Mapping of Protostellar nebulae

C. Mapping of Supernova remnants (particle acceleration)

IV. Stellar

A. Detection of photospheres/chromospheres in many types of stars.

B. Spectra of stellar wind sources, other mass loss.

V. Solar System

A. Composition of the surfaces of planets, satellites and asteroids.

B. Nuclei of Comets

C. Rings of Saturn

D. Upper atmospheres of Giant Planets

A millimeter array offers numerous exciting possibilities for continuum work. Advantages over single dishes of similar total collecting areas include 1) higher spacial resolution, 2) more sensitivity due to the possibility of longer integration times and 3) faster mapping of extended sources due to the larger field of view of an array. Resolutions from scales of about an arcminute possibly down to a tenth of an arcsecond should be possible. Integrations times of 10 hours and longer should be routine with an array while millimeter continuum measurements with single dishes usually are limited to less than an hour before dc fluctuations and ground pickup becomes a problem. An array of 6 meter dishes would have about 17 times the field of view of a single 25 meter telescope with these clear advantages an array offers numerous exciting opportunities in the millimeter array of the spectrum. Summarized below are a few of the types of the continuum projects which would be carried out with a millimeter array.

Cosmological problems offer some of the best possibilities for new results. Among the most exciting is the possibility of combining x-ray and millimeter observations of the hot gas in rich clusters to determine the distance of the clusters directly. The thermal bremstrahlung x-ray emission for clusters is proportional to the $\int n_e^2 T^{-\frac{1}{2}}\, dl$. The same gas produces a decrement in the 3K background emission proportional to $\int n_e T dl$. This decrement is most easily observable near a wavelength of 3 mm. The x-ray data from AXAF should yield the temperature of the gas. When maps of the emission in both the x-ray and millimeter are combined because of the difference in the dependence on n_e the distance can be derived without any use of other distance indicators. Once the distances are combined with the redshifts for a range of distances q_o and H_o can be derived.

At least two other cosmologically interesting measurements may be possible. First the anisotropy in the 3K background on scales of arcminutes to arcseconds can more accurately measured with a millimeter array than any other ground based technique. Second, and less certain, high redshift protogalaxies may be observable due to redshifted dust emission. In fact at redshifts >3 it may turn out that confusion with closer by galaxies may prevent detection of very high redshift galaxies except at wavelengths > 300μ and at resolutions on the order of one arcsecond.

Many other extragalactic projects of more physical than cosmological interest are also possible with a millimeter array. Particle acceleration in extended radio galaxies can be studied from high frequency spectral mapping. The spectra and polarization of the central components of radio galaxies also provides us with one important due to the origin of the activity in galactic nuclei. An array 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 millimeter wavelengths. Used like the VLA a millimeter array would certainly provide to largest collecting area for frequencies >50 GHz in the U.S. and thus would extend the possibilities for millimeter VLBI.

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

Another class of extragalactic problem is the study of the relation of dust, gas, and relativistic particles in normal galaxies. All three produce emission in the 1-10 mm window. The dust spectrum is falling off from its peak in the far infrared near 1 mm. The nonthermal emission is often dominant longward of 1 cm. Thermal free-free emission often dominates between these two parts of the spectrum. Thus by mapping the spectrum of emission in the millimeter region and using data from other frequencies one should be able to separate and study each process.

Interesting galactic projects can also be carried out with an array in the millimeter region. 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 be actually be mapped at 0.1 to 1.0 arcsecond 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.

Many stellar projects are also possible due to the resolution and sensitive of an array. The photospheres and chronospheres 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. These results suggests that large numbers of giants and supergiants should have detectable emission in the range of sensitivity of the millimeter array. Thus studies of the photospheres/chromospheres of these and other anamolously excited stars should be possible for the first time.

VLA mapping of hot stellar wind objects and proto-planetary nebulae are providing structural and other physical information. However, with a millimeter array 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 redsupergiant winds and the socalled "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 a millimeter array would produce a much clearer understanding of the stellar evolution of stars in the upper part of the HR diagram.

Solar system work will also be important with a millimeter array because almost all the objects in our planetary system emit thermal radiation. The composition of a wide variety of objects (including planets, satellites and asteriods) can be studied from the observed spectrum and dirurnal variability. Centimeter wavelengths probe too deeply to see temperature changes in most cases while the infrared properties apply only to the very surface. Objects down to diameters of 20 km may be observable in the asteroid belt.

The nuclei of comets should be also observable based on current theory. Recent data suggests that the millimeter emission from the rings of Saturn does not fit a simple thermal model and thus complete two dimensional observations at a variety of phase angles and ring orientation are needed to compliment existing ground based and satellite data. In the giant planets capacity due to ammonia is thought to dominate longward of one centimeter; however, at millimeter wavelenghts hydrogen opactic becomes important. Thus millimeter continuum observations should yield new data or the relationship of these two atmospheric components.

These are just a few examples of areas in which a millimeter array would add significantly to our understanding of astrophysics in the continuum. It is far from exaustive. Clearly such a project would contribute to almost all areas of astronomy.

FNO/bmg

Science Proposals
for the
Next Generation of Millimeter-Wave Telescopes:
The Formation of
Stars and Planetary Systems

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I. Introduction

STAR FORMATION IN THE COLD UNIVERSE

During the last decade the development of millimeter-wave and infrared astronomy has for the first time ever, enabled astronomers to explore and directly probe the cold universe, a universe rich in astrophysical complexity, activity and mystery. The result of this exploration has been, a revolution in our understanding of star formation and the interstellar medium. A major break through in this endeavor occured in the early 1970's with the discovery of giant molecular clouds (GMCs) as a result of millimeter-wave spectral line studies of the carbon monoxide molecule. With sizes often in excess of 100 parsecs and masses between 100,000 and 1,000,000 suns, GMCs are the largest and most massive objects in the galaxy, yet only 10 years ago their existance was unknown to astronomers. Now it is believed that most of the interstellar material in the galaxy resides in complexes of such molecular clouds. Consisting mostly of molecular hydrogen, these clouds have temperatures in the range between 10 and 100K and are probably the coldest objects in the galaxy. Infrared observations have shown them to be the primary sites of star birth in the galaxy.

The detection and subsequent study of interstellar molecular gas has enabled us to obtain the first detailed glimpses into the physical processes occuring 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 phenonemon known from optical infrared, radio and millimeter-wave 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 millimeter wavelengths; as extended regions of hot, shocked molecular gas in the near-infrared; as high velocity H_2O maser knots at centimeter 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 ultra-violet 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 centimeter-wave 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 nebulae 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 desrupting 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 new global view of star formation and with detailed information about the temperatures, densities and energetics of molecular gas and dust directly provided by millimeter-wave and infrared observations, the beginnings of a theoretical foundation for understanding the star formation process is being developped, tested and refined. For example, one recent theory, suggests that the internal structure of OB associations can be explained if massive stars are formed in sequential bursts within a giant molecular cloud. Ionization of the parental cloud by a 1st generation of massive stars drives a shock wave into the cloud which compresses the gas to a density in excess of the critical value for gravitational instability. The shock compressed region collapses and fragments forming a second generation of massive stars. In turn these stars ionize surrounding material, produce shock waves and trigger the birth of a third generation of stars. In this way a wave of successive star formation events propagates through an elongated giant molecular cloud complex. Support for this theory comes from optical observations of OB stars, and infrared, radio and millimeter-wave observations of molecular clouds. Another theory suggests a symbiotic relationship between newly formed stars and the longevity of molecular clouds. Even though the onset of massive star formation results in the gradual destruction of GMCs, the process takes at least a few tens of millions of years. Yet, the temperature of molecular clouds are too low to support them against complete global gravitational collapse, a process which would eradicate the clouds within only a few million years. According to this second theory, low mass stars formed throughout a giant molecular cloud volume deposit mechanical energy into the cloud through stellar winds. The turbulence generated by stellar winds provides support against the gravitational collapse of clouds. The process may even couple with low mass star formation and be self-regulating. Support for this theory comes from the observation that low mass star formation is widespread through GMCs and from the recent important discovery that early in their lives most stars produce very energetic stellar winds which interact directly with surrounding molecular gas.

The power of mm-wave 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 100 species of molecules and radicals provides mm-wave 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 measure temperature, density, or column density of molecular clouds; others can be used to probe the fractional ionization of the gas; still others can be used to study its isotopic composition. By chosing 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 mm 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 directly study the material which forms of stars and planets, fuels active galaxies, and perhaps provides the chemical foundation of life itself.

The opening of the cold universe to exploration by millimeter-wave 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 universe. And this can only be accomplished through continual development of and improvement in millimeter, submillimeter and infrared wavelength observational capabilities.

II. Outstanding Problems in Star Formation

THE PHYSICAL NATURE OF MOLECULAR CLOUDS

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 both varied molecular lines and observations 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. We need to build instruments with resolving powers one to two orders of magnitude greater. Since we expect both the density and temperature of a proto-stellar fragment to increase as the fragment becomes smaller and smaller in size, higher frequency spectral line observations, particularly in the submillimeter and far-infrared, are essential to studies of the small proto-stellar environment.

Detailed knowledge of the dynamical state of molecular clouds is of critical importance to the understanding the process of star birth and the evolution of the clouds. Why do molucular clouds survive over timescales longer than the gravitational free fall colapse time? Why are molecular cloud spectral lines so broad? To what degree is the observed velocity structure due to turbulence or to systematic motion? What generates turbulence in molecular clouds? Why have collapsing regions not yet been identified? Significant progress toward answering these questions requires observations which resolve the turbulent elements of molecular clouds and observations which measure the velocity structure of molecular gas over a wide range of physical dimensions. Higher angular resolution mm-wave instrumentation is needed. For example, a large collecting area interferometric instrument will have a unique ability to probe the kinematic and spatial structure of molecular clouds by observing molecular *absorption* lines seen against background radio-continuum sources such as distant quasars. For sufficintly large dish spacings, interferometry "resolves out" smoothly distributed gas, rendering the spectral line emission which normally fills in the absorption profile, invisible. The absorption line is formed by gas lying only in the direct line of sight to the background source. Distant quasars, whose mm-wavelength emitting cores are probably micro-arcseconds in angular diameter, probe the intervening molecular gas with a pencil beam only 10^{-3} AU ($=10^{6}$ km) wide at a distance of 1 kpc!!

MOLECULAR CLOUD FORMATION AND THE EVOLUTION OF GALAXIES

Since stars form in molecular clouds an understanding of star formation will inevitably be closely tied to an understanding of the formation and evolution of molecular clouds themselves. We do not know how molecular clouds form. An understanding requires a global perspective; we need to know cloud lifetimes; their relation to spiral arms; and how they evolve chemically. Spiral structure in galaxies is delineated by the luminous, recently formed O-type stars; spiral arms trace the regions undergoing the most vigorous star formation in the entire galaxy. Does star formation occur in spiral arms because the molecular clouds are *formed* in the arms? Or do global spiral shocks in the interstellar gas merely ignite energetic bursts of star formation when a pre-existing cloud pases through an arm? One theory suggests that the very existance of global spiral structure in galaxies is a result of self-propagating star formation. In this picure, star formation in one region initiates star formation in neighboring regions; the diferntial rotation of the galactic disc distorts the propagating star formation wave into a spiral pattern. We need to map the distribution of molecular gas in many galaxies with arc-second resolution in order to understand the the relation between spiral structure, formation of clouds, and star formation. Since molecular cloud formation and evolution controls star formation in a galaxy, the evolution of galaxies themselves is critically tied to the evolution of molecular clouds. *Studies of the molecular component of external galaxies is the single most important endeavor to be pursued in star formation research during the upcoming decade.* It is of utmost importance to study the galactic distribution of molecular clouds, the total molecular content, and the mass spectrum of molecular clouds as a function of galaxy type. Studies of the molecular component of external galaxies will also enable us to assess the importance of molecular clouds and star formation in fueling activity in active galactic nuclei. Does the gravitational infall of cold gas onto a neucleus of a galaxy result in a "star burst", in which massive stars form at an enourmous rate. Does the accretion of molecular gas onto compact objects in a galactic core generate Seyfert or QSO activity?

The interstellar medium is the active component 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 controling 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 (such as galaxy-galaxy collisions). Star formation can control the chemical evolution of galaxies. Which thermoneuclear processes dominate elemental enrichment? By studying the isotopic composition of molecular clouds in galaxies and their abundance gradients, we may be able to untangle the webb of intricate processes which control the evolution of galaxies. The problem of molecular clouds and star formation in external galaxies can only be solved with an intense observational effort with a new generation of instruments. High sensitivity and high angular resolution observations are required, this in turn requires new telescopes with large collecting areas.

ENERGETIC MOLECULAR OUTFLOWS FROM YOUNG STELLAR OBJECTS

One of the most recent and exciting discoveries made by millimeter-wave CO observations is the detection of massive and energetic molecular outflows around very young stars. The existance of such energetic and outflows of cold material was totally unexpected and the high frequency of occurance of the phenonema 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 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 collinated 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 property of astrophysical systems with vastly different physical parameters.

The molecular outflows may provide us with unique opportunities to study the physics of jet formation in a way not possible for extragalactic jets. We can directly determine the velocity structure of the molecular jets from the doppler shift of the spectral line profiles. Velocity information is not available for extragalactic radio sources. In addition, the molecular jet sources are within our galaxy; because of this proximity high resolution infrared and millimeter-wave spectral line observations may directly probe the driving "engine". We can in principle determine the physical conditions near the central object where the jets are accelerated and collimated. Since not all the molecular jets are well-collinated and a few outflows are completely spatially symmetric, the conditions necessary for jet collination are not present in all sources. Studying differences in physical conditions between uncollinated and collinated outflows could lead to a model for jet formation.

The discovery of bipolar molecular mass outflow in star formation regions may tie together several apparently unrelated phenonema 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 masers and Herbig-Haro objects show large proper motions away from highly obscurred young stars. Observations of these sources may provide us with an ideal laboratory for studying the physics and chemistry of interstellar shock waves.

INTERSTELLAR DISCS AND THE FORMATION OF PLANETARY SYSTEMS

For hundreds of years it has been suspected that the Solar System formed from the gravitational collapse and self-accretion of a gas disc surrounding the proto-Sun. Recently, radio and infrared spectroscopy as well as aperture synthesis mapping has provided the first observational evidence for massive discs of gas and dust around newly formed stars. A torus of very dense gas has been observed around one of the highly obscurred, luminous infrared stars buried behind the Orion Nebula. The orientation of this disc suggests that it may confine the high velocity outflow blowing from the core of the Orion Molecular Cloud into two oppositelly directed jets. Evidence is mounting that many of the bipolar molecular outlfows are confined by discs surrounding the stars responsible for the driving wind. There is evidence for discs surrounding the exciting stars of some optically visible bipolar nebulae. A good example is the HII region S106, whose exciting star appears to be surrounded by a shadow in radio images of the ionized gas. The "shadow" seems to mark the presence of a dense and dusty circumstellar disc, sufficiently opaque to ionizing ultraviolet radiation to prevent any gas from being ionized in its geometric shadow. These discs of gas may be the sites of formation for planetary bodies associated with a newly formed star.

The investigation of the imediate circumstellar environment of newly formed stars in the nearest molecular clouds poses great challenges for the next decades. For clouds lying within a few hundred pc of the sun an instrument with slightly better that one arc-second resolution can resolve the proto-planetary disc around a newly forming star. The density, temperature, and chemical structure of such discs will provide vital information on the birth of planetary systems. Large individual proto-planetary condensations may be within the reach of such an instrument. Perhaps we may even learn of the processes that give rise to cometary systems, such as the Oort Cloud surrounding our Sun. The opportunity to observe another planetary system in the process of formation around a nearby star would be one of the most exciting scientific endeavors ever undertaken.

THE GALACTIC CENTER

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 proudced 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, Sag 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 kinnematics 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 presently available arc-minute diameter mm-wave 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.

FUTURE PROSPECTS AND OPPORTUNITIES

The quest to understand star formation has had an inspiring start with the development of millimeter-wave and infrared astromony. However we have only begun to appreciate the complexity, importance and excitement of the future of this area of astrophysical endeavor. The wealth of significant results uncovered within the last decade compels us to energeticly pursue these problems with the development and utilization of new observational facilities in space and on the ground. In particular we need to develop the relatively untouched submillimeter portion of the spectrum and construct instruments with large collecting area and high resolving power at millimeter-wavelengths. At the present time a number of such facilities are either built or contemplated for infrared and submillimeter observations in the United States. These include two infrared space observatories IRAS and SIRTF, which should produce high sensitivity far infrared surveys of the entire sky. On the ground moderate aperture (10-meter) submillimeter telescopes are being developed by Cal. Tech. and the University of Arizona in collaboration with the Max Planck Institute for Radio Astronomy in Germany. A new 12-meter surface has been installed on the NRAO millimeter-wave facility in Arizona to enable spectral line observations at wavelengths as short as 1 μm. NASA is contemplating a large aperture far-infrared-submillimeter telescope for deployment in space in the late 1990's or early 21st century known as the Large Deployable Reflector (LDR). All these efforts should be encouraged and supported by the astronomical community. In Europe new millimeter-wave facilities are nearly operational at λ 3 mm. In addition two and three element interferometers are being constructed in France, Japan and California for operation in the millimeter-wave range.

These instruments should greatly improve our ability to probe regions of star formation. However two vitally important observational capabilities are not addressed by these instruments and need to be promptly and seriously considered. First, there is a strong scientific need for a 10-meter class millimeter-wave facility in the Southern Hemisphere. The southern hemisphere offers the best access to the central regions of the Milky-Way and the only access to the Magellenic Clouds, the nearest galaxies and external star forming systems to our the Milky-Way. Despite the critical nature of millimeter and infrared observations, star formation is a problem that bridges all wavelength bands. The infrared space missions and the space telescope will explore the whole sky and investigate star forming regions in the southern Milky Way and Magellenic Clouds. Without complementary millimeter-wave observations such investigations will be fundamentaly limited in their scope. The need for a Southern Hemisphere facility is more pressing now than ever before.

Second, a large aperture, high angular resolution millimeter-wave facility is still not available. A facility with the collecting area equivalent to a 30-50 meter telescope and angular resolving power of better than 1 arc sec is now technologically possible. A millimeter-wave aperture synthesis array would be the most powerful instrument for star formation studies ever built. It would provide imaging capibility of the cold component of external galaxies and our Milky Way with a resolution better than the best ground based optical telescopes. Constructing such an instrument is of the highest priority for star formation and millimeter wave studies.

With the development of a southern hemisphere facility, a millimeter-wave aperture synthesis array, ground based submillimeter telescope and the LDR, the Astronomical Community in the United States could maintain its position as the world's leader in star formation research well into the 21st century.

Appendix 1

OBJECTS VISIBLE WITH AN APERTURE SYNTHESIS ARRAY

Type of Source	Physical Size	Maximum Distance at which Detectable	Detectable within the Volume Occupied by ...
Small proro-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 galaxies
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

The above table is based on a mm-wave array consisting of 30 6-meter diameter dishes (Total collecting area = $848 m^2$) and equipped with receivers giving $T_{sys} = 200K$. The overall sensitivity of such a system is given by

$$\Delta T_{rms} = 0.1 \left[\frac{\lambda}{1mm}\right]^2 \left[\frac{\vartheta}{1arc-sec}\right]^{-2} \left[\frac{\Delta\nu}{1MHz}\right]^{-0.5} \left[\frac{t}{12hours}\right]^{-0.5}$$

in degrees Kelvin. Here, λ is the wavelength being observed, ϑ is the synthesized beam diameter, $\Delta\nu$ is the bandwidth of each channel in the spectrometer, and t is the integration time. One MHz resolution corresponds to $1 kms^{-1}$ at 1mm.

Appendix 2

ASTROPHYSICAL PROBLEMS THAT REQUIRE HIGH ANGULAR RESOLUTION mm-WAVELENGTH STUDIES

OUTLINE

Extragalactic Astronomy

Structure of Galaxies

mm-wavelength synthesis of the distribution of molecular gas in galaxies will provide detailed information on the behavior of the active component of the interstellar medium. Studies of the various isotopic varieties will provide a direct probe of galactic abundance gradients and galactic evolution. Arc-second resolution will let us study distribution of molecular gas in spiral arms. This provides us with the best opportunity to understand spiral structure, the formation of clouds and hot stars in spiral arms, and the variation of spiral morphology with galaxy type.

Quasars and Extragalactic Radio Sources

Study the structure, polarization, spectra, and time variability of centimeter excess sources. These tend to be the most active extragalactic radio sources; mm-wave study at high angular resolution will shed light on the radio evolution of the synchrotron sources and the nature of the quasar phenomona. Molecular absorption lines seen against the continuum spectrum of the quasars may provide a powerful probe of the dense gas in active neuclei. Application to sources buried in edge-on galaxies at high red-shifts, may provide information on the evolution of the molecular content of galaxies as the universe expands.

Sunayev-Zeldovich Effect

We can probe the nature of the intergalactic medium by measurement of the diminuition of the the 3K microwave background in the direction of rich clusters of galaxies. This effect is caused by the inverse-compton scattering of microwave photons by electrons in the x-ray emitting plasma contained within many clusters of galaxies. Comparison of the radio effect with measurements of the x-ray properties of the cluster gas as measured by the proposed AXAF satellite will lead to an accurate determination of expansion rate of the Universe.

Galactic Neuclei

The study of both molecular line and radio continuum emission from the neuclei of galaxies will provide insight into the nature of violent neuclear activity. Molecular emission provides both a convenient tracer of the kinematics and potential fuel for activity.

Galactic Astronomy

Structure of Molecular Clouds

In our galaxy molecular clouds contain most of the mass of the interstellar medium out of which new generations of stars form. Aperture synthesis will alow detailed study of their structure; are they smooth or clumped?

Interstellar Shock Waves

Shock waves caused by supernovae, the expansion of HII regions, and stellar and protostellar mass loss may dominate the chemistry and kinematics of molecular clouds. Arc-second resolution will allow us to study the chemical and physical processes that occur in the thin post-shock layers.

The Galactic Center

High resolution study of the molecular component of the Galactic Center is essential to understanding its kinematics and morphology. The nature of the interstellar medium in this region is very different from the rest of the Galaxy.

Planet and Star Formation

Detailed study of the processes responsible for the formation of planets and stars will be possible when arc-second angular resolution is made available to mm-wavelength astronomers. Study of the molecular gas component will enable us to probe the detailed physics and chemistry of the star forming environment which is rendered invisible at optical and near-infrared wavelengths by the dust contained within the gas.

Formation of Planetary Systems

With high angular resolution, the structure of the gas discs beleived to be responsible for the formation of planets can be studied. Structures such as the Oort Cloud which contain the Solar Systems population of comets will be resolved in the nearest star forming clouds.

Stars

Many stars have massive stellar winds. For stars with ionized winds, the radio flux increases toward higher frequencies so a mm-wavelength array is the best was to study the continuum emission of these stars. Energetic mass loss has been observed to be associated with both stellar birth and stellar death. Aperture synthesis of the molecular emission lines associated with late type stars will enable us to probe the detailed structure of the stellar photospheres and the wind acceleration region. Much can be learned about the chemical and isotopic enrichment of the interstellar medium and the Galaxy by studying mass loss from dying stars.

Bipolar Nebulae

Many stars in their death, expell a sizable fraction of their mass, returning freshly synthesized elements to the interstellar medium. Frequently, the mass is lost in molecular form, forming large circumstellar enveloppes that can be studies in the mm-wave window. In addition to proto-planetary nebulae, bipolar nebulae, symbiotic stars, and slow novae may be exciting sources to study with a high resolution mm-wave instrument.

Solar system Astronomy

The Sun

Detailed investigation of solar phenomona such as flares in the mm-wave continuum is possible. Some molecules may be present in the solar reversing layer; high resolution spectroscopy of mm-wave absorption features made possible by heterodyne methods may provide a detailed probe of solar vibrations.

The Planets

The discs of all the major planets will be resloved by a mm-wave array. Study of molecular transitions will provide a probe of weather patterns and seasonal variations in the chemical composition of planetary atmospheres.

Comets and Asteroids

Non planetary solar system objects such as asteroids and comets can be imaged with a mm-wave sysnthesis array. In addition to the thermal continuum radiation from these bodies, spectral lines in comets will provides powerful high resolution probes of their physics and chemistry.

The Molecular Component of the Galaxy

The detection of millimeter wavelength emission from CO widely distributed throughout our galaxy has had a profound influence on our view of the distribution of matter in the galaxy. During the past 30 years our understanding of the structure of our galaxy has been based, to a large extent, on observations of the 21 cm line of neutral hydrogen, the component which allowed us to "see", for the first time, past the obscuring dust in the solar neighborhood. We now find that, in the inner part of the galaxy, the HI distribution is distinctly different from that of the other indicators of structure. Within the solar circle, much of the gas is in the form of molecular hydrogen compressed into cloud complexes, Giant Molecular Clouds with sizes ranging up to 80 pc in diameter and masses up to a million suns. Regions of active star formation are associated with these complexes as are the concommittant giant HII regions, supernova remnants, and intensity peaks in the gamma-ray emission.

Although CO is the most abundant molecule after H_2 and, probably, H_2O and therefore the most easily detected, the millimeter spectral region is rich in the emission lines of many other molecules. Dozens of molecules, many quite complex, have been detected. These provide important evidence of the cloud chemistry and physical properties as well as the galactic distribution of the different atomic species and their isotopes.

The giant molecular clouds are the most massive objects in the galaxy, exceeding even the globular cluster in mass. They are bound closely to the disk and lie mainly in an annulus between 4 and 8 kpc. The detailed CO maps, just coming out, of nearby regions show in an impressive way the connections between the various signposts of star formation: HII regions, H-H objects,masers, reflection nebulae,and dark cloud material. All are contained by the molecular clouds.

Research at millimeter wavelengths is in an early phase, and there are many crucial questions that can only be answered by further work. How well and in what way do the molecular clouds show spiral structure? How do the giant clouds form? Is it by accretion or the compression of spiral density waves? What are their lifetimes? The available evidence calls for lifetimes that are one hundred times the free-fall collapse times. Indeed, if they all collapsed to form stars on free-fall time scales, the star formation rate would be too high by a factor of one hundred. Why does the galactic gas content fall rapidly within 4 kpc. of the center? What is the radial distribution of the various atomic species and their isotopes? What is the overall distribution of mass within the galaxy? CO observations have already permitted the extention of the galactic rotation curve to greater distances than possible before.

We have only partial answers to these important large scale questions. They must be addressed by observations of millimeter line emission of various molecules on very large scales. The angular resolution of single reflector telescopes is appropriate for this work, and it is crucial that such telescopes be adequately supported to carry out this important program. The kind of technical progress that will particularly benefit this work will be the development of array receivers for the telescope focal plane, that is, multibeam capability. The examination of large sections of the galaxy with a resolution of one arc minute (in several molecular lines) is otherwise a very protracted program.

There is also a large class of problems which require higher angular resolution. What is the strength and distribution of the magnetic field within a typical giant cloud? Is it adequate to support the cloud? At what density in a collapsing core is the ionisation so small that the magnetic field is no longer important? What is the distribution of angular momentum within a typical cloud and what may be its influence on the cloud stability? These high resolution studies naturally lead to the detailed investigation of star formation in molecular clouds. The instrument required for high resolution work is, of course, an array. The available evidence suggests that one can carry out aperture synthesis quasi-routinely with resolution as good as 0.1" at millimeter wavelengths.

The large scale questions about our galaxy may only be answered in the course of investigations of other galaxies, where our perspective is better. Although quantitative studies of the emission from other galaxies is a recent activity, the results are already quite impressive. For example, the difficiency in molecular gas within the 2-4 kpc. region in our galaxy is apparently not a common characteristic of the other spiral galaxies so far observed. It is clear from the work done to date that the angular resolution needed for extragalactic observations requires an array. The ≈1' beam of the single reflector is not adequate.

W J Welch

ASTRONOMY WITH THE MMA (Knapp)

(a) Assumptions:
16 x 6 meter dishes, maximum baseline 3 km, efficiency = 65%

At 2.6 mm, field of view = 2 arcmin and maximum resolution = 0.2 arcsec

T(SSB) = 400 K, int time = 10 hours, bandwidth = 1 MHz (line), and 1 GHz (continuum).
in 1" x 1" pixel, T(rms) = 2.5 K (line)
in continuum S(rms) = 10^{-4} Jy.
positional accuracy for strong non-thermal sources > 0.05".

(b) Resolution:

1" at various distances is:

D	1" =	Objects
1 a.u.	700 km	solar system
50 pc	7.5×10^{14} cm, 50 a.u.	Taurus clouds, o Ceti, Hyades
200 pc	3.0×10^{15} cm, 200 a.u.	Oph clouds, IRC+10216, α Ori, other stars and dark clouds
500 pc	7.5×10^{15} cm, 500 a.u.	Orion molecular cloud
1 kpc	1.5×10^{16} cm, 10^4 a.u.	Local GMC's, spiral arm, CRL2688 et al.
10 kpc	1.5×10^{17} cm, 0.05 pc	Galactic center, Galactic objects, e.g. W49
1 Mpc	1.5×10^{19} cm, 5 pc	Local Group inc M31
15 Mpc	2×10^{20} cm, 75 pc	Virgo cluster

(c) Continuum projects

Solar limb
Solar granulation, spicules
Coronal structure
planet and satellite surface temperatures
Saturn's rings
protostars in HII regions and molecular clouds
very compact HII regions
sharp fronts in HII regions
dust emission from HII regions (1 mm)
winds from T Tau stars
accretion disks around young stars and protostars
winds from early-type stars
chromospheres, winds and surface temperatures of late-type giants
dust in cs envelopes
structure of young planetary nebulae (e.g. CRL618)
inner structure of PN's with binary nuclei.

filaments in snr's
active galactic nuclei
inner structure of jets
hot dust in active galaxies e.g. M82
quasar monitoring and spectra
microwave decrement towards x-ray clusters
small-scale structure in microwave background

(d) Line projects

Venus and Mars; molecule searches and day-night effects in abundances
Outer planets; molecule searches
photochemistry in comets
molecule searches
filling factors and clumping in molecular clouds of various types
shapes and dynamics of clumps
filling factors in dense molecular cloud cores
structure of self-absorption regions: temperature gradients and filling factors
locations of weak methanol masers
chemistry across bright rims
detailed chemistry in molecular cloud cores
recombination lines in BN type objects - velocity widths
molecular absorption against continuum sources
structure of thin gas layers near snr's, and abundances therein
structure of wide-wing sources and disks
possible distant wide wing sources, e.g. W49
polarization and magnetic fields
CS envelopes: structure and distribution of SiO masers
T(CO) vs r - heating and cooling
envelope radii and $\dot{M}$
inner structure of envelopes around single stars (e.g. IRC+10216(?)) vs BPN's, e.g. CRL2688
envelope radii in various molecules; photo-chemistry and self-shielding
individual GMC's in M31; association with dust, HII regions,
spiral arms, HI. How much of total CO flux is in individual clouds?
Spiral structure in nearby galaxies out to Virgo cluster distance
molecular gas in Seyferts and active galaxies
structure of peculiar galaxies
association of GMC's with star formation on a large scale

Chemistry Studies with a Large Millimeter Array

Bill Langer

Spin offs through different types of chemistry on smaller scales.

The past decade has witnessed a revolution in our understanding of the interstellar medium largely as a result of radio observations of millimeter 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 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 chemsitry can provide important information about our understanding of chemical reactions. Indeed, many suggestions originally made to explain molecular abundances in clouds stimulated laboratory researches 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 $C^+ + H_2$ -- CH_2^+ + photon, or $H_3^+ + O$ -- $OH^+ + H_2$, 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 chemsitry 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 (Graedel, Langer, and Frerking 1982), 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. It is for such regions that the large millimeter array is needed. Below are discussed several other phenomena where this instrument is necessary. Around evolved stars, in shocked molecular gas, and where UV radiation is present chemical abundances change significantly over small distances. A high resolution millimeter array is needed to test the detailed models of the chemistry of these regions.

Circumstellar envelopes around red giants are rich in molecular species and are observed to be strong emitters of molecular radiation at millimeter wavelengths. These envelopes are the result of mass loss from the star and are important sources of gas for replenishing the interstellar medium. The study of the envelopes is also important to the evolution of these stars, which are precursors of planetary nebula and supernova. Over twenty molecules have been detected in the circumstellar envelope of IRC+10216, including many exotic species such as the long chain ~~[illegible]~~ polycyanoacetylenes. However, no molecular ions are found in this source and ,hence, ion molecule chemistry is not important here. Instead it has been suggested that a freeze-out model applies in which chemical equilibrium is present near the photosphere, and in the circumstellar shell the density and temperature drop rapidly enough that further chemical reactions are unimportant (c.f. the review by Zuckerman, 1980). At present these models do not yield the correct abundances for many species, for example, NH_3 and CN. Furthermore, photodestruction by UV radiation, which surrounds the star, must be included. The example of CO is a good case in point for the need to do high resolution studies of circumstellar envelopes in order to understand the chemistry and history of the stars mass loss.

CO maps of IRC+10216 show that emission extends out about 3' with significant variation of a scale size of the antenna beam (40"). Since the distribution in outflowing material can be related to the mass loss rate as a function of time these relults indicate that mass loss rate has changed with time over the age of the shell (about 10^4 years). Obviously observations at a higher resolution, better than 15", would be important. The same is true for understanding the chemistry of CO in circumstellar envelopes.

Models of the CO abundance depend sensitivelyon the mechanisms for CO photodissociation, which are poorly understood at present because of a lack of laboratory measurements (the UV spectroscopy of CO is difficult to do at present). In particular it has been argued that self-shielding of CO photodissociating radiation is important for CO abundance profiles (Bally and Langer, 1982) and that this is true for outflows in late type stars (Morris and Jura) Models based on different assumptions result in vastly different profiles from $5x10^{17}$ to $5x10^{18}$ cm. To test these models requires the high resolution observations of CO discussed above (Other molecules should have different profiles).

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 (eg. Langer; Mitchell, Ginzburg, and Kuntz; Prasad and Huntress) show that molecular abundances vary by orders 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 with 1' to 2' for a source at ~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 (Young et al.) 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. A high resolution millimeter telescope has sufficient resolution to study the models of photochemistry in molecular clouds.

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 infrared) lines of molecules provide a unique probe with which to determine the properties of shocks.

Chemical abundances in the shocked gas are quite different from those in the surrounding cloud, or preshock gas, as can be seen in high velocity wings of molecular lines (Zuckerman and Palmer 1975). The chemistry in shocks is different from the surrounding cloud because the high kinetic temperatures in the shock allow neutral reactions with large activation barriers, especially those involving H_2, to occur rapidly (for example, $O+H_2 \rightarrow OH+H_2$). Model calculations show that preshock abundances can be enhanced, reduced, or unchanged, depending on the species and the physical conditions in the shock (eg. velocity, magnetic field strength). At present theory and observation are not always in accord, for example, Hartquist, Oppenheimer, and Dalgarno (1980) predict that CS increases significantly in shocks, yet Goldsmith et al. (1980) did not find such large increases in Orion.

Supernova remnants also produce shocked molecular gas and observations of regions such as IC443 confirm this. DeNoyer and Frerking (1981) found no enhancement in HCN, CS, SO, or SiO in this shock, in contrast to the high velocity component (shock) observed in Orion. Furthermore, they observe an increase in the ratio of HCO^+ to CO which disagrees with the model calculations of Iglesias and Silk.

Shock models have also been invoked to explain molecular abundances in diffuse regions, such as the gas towards ζ Ophiuchi (Elitzur and Watson 1978, 1980). Despite the initial success of these models in explaining CH^+ abundances there are problems with other species.

The passage of a shock through a cloud changes the chemical abundances of the preshock gas because of the high temperatures and densities in the shock. Molecules can be dissociated in shocks, but also reactions of atoms with H_2 which have activation barriers may proceed rapidly. The chemistry of shocks is important for analyzing and modeling shocks; molecular cooling, for example, is important in the evolution of a shock, and it depends in part on the molecular abundances.

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 ~5×10^{15} cm according to the models of Draine, Roberge, and Dalgarno (1983). At the distance of Orion, ~500 pc a resolution of ~5″ is needed to study its structure. The importance of shocks and shock chemistry in interstellar clouds cannot be underestimated. 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 a large millimeter array. So too is an understanding of circumstellar envelopes and regions with photochemistry. If the past history of ion molecule chemistry is any indication an understanding of the chemistry in these regions will reveal much about the sources, stimulate new laboratory research, and test ~~conditions~~ calculations of chemical reaction theory.

COMPLEX GALACTIC MOLECULES
AND THE
NEXT GENERATION OF MILLIMETER-WAVE TELESCOPES

L. E. Snyder

1. GALACTIC MOLECULES: AN OVERVIEW

   A. Interstellar Molecules

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   C. Interstellar Masers

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   B. Are there undetected keystone molecules?

   C. How are galactic molecules related to star formation?

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3. MOLECULAR RESEARCH WITH THE NEXT GENERATION OF MILLIMETER INSTRUMENTATION

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1. GALACTIC MOLECULES: AN OVERVIEW

In the past decade, molecular radio astronomy has progressed significantly in the areas of new molecular detections, stellar masers, identification of interstellar molecules not measured in the laboratory, interpreting isotopic abundance measurements, and radio spectroscopy of comets. As of mid-1982, 56 galactic molecular species had been reported and are listed in Table 1. More than 400 molecular transitions have been reported in the region of the spectrum from 834 MHz through 346 GHz and beyond. A list of transitions and their recommended rest frequencies published in 1979 by Lovas, Snyder and Johnson (1979 Ap. J. Suppl., 41, 451) is rapidly becoming dated. It is generally accepted that radiative transfer by molecules (especially the simple and abundant species) is important for the necessary cooling of galactic clouds which allows contraction to proceed and possibly results in star formation. A class of OH and H_2O masers is thought to mark protostellar regions. It has been proposed that the final step in star formation, the solar nebula stage, may be directly observable in several objects via the SiO maser.

It is now accepted that no single formation scheme will be able to realistically account for the molecules in Table 1 but one proposed scheme, ion-molecule formation, could explain the formation of many small species at low temperatures. The widespread galactic distribution of HCO^+ and HNC, and the unusually strong intensities of several deuterated molecular species relative to the intensities of their normal isotopes in dark dust clouds are considered to be evidence supporting theories of ion-molecule formation. The detections of new circumstellar HC_3N sources show that long-chain carbon molecules can be observed easily in evolved stars but no direct link between circumstellar shells and dark clouds has been established yet.

Table 1. The 56 known interstellar molecules

listed in order by number of atoms

2	3	4	5	6	7	8	9	11	13
CN	H_2O	NH_3	HC_3N	CH_3CN	$HCOCH_3$	$HCOOCH_3$	CH_3CH_2OH	HC_9N	$HC_{11}N$*
CH	HCN	H_2CO	HCOOH	$HCONH_2$	NH_2CH_3		$(CH_3)_2O$		
CH^+	HCO^+	H_2CS	H_2CNH	CH_3OH	CH_2CHCN		CH_3CH_2CN		
H_2	HNC	HNCO	H_2NCN	CH_3SH	CH_3C_2H		HC_7N		
OH	OCS	C_3N	H_2C_2O		HC_5N				
CO	H_2S	HNCS	C_4H						
CS	SO_2								
SiO	C_2H								
SO	N_2H^+								
SiS	HCO								
NS	HNO								
C_2	HCS^+								
NO	O_3								
	HOC^+								
	NaOH								

*Observed only in IRC+10216

L. SNYDER 1982

Radio spectroscopy of comets is still a relatively new area of investigation but considerable progress has been made in understanding the radio observations of cometary OH In section D, it will be shown how these OH studies suggest that important millimeter-wave observations remain to be made as the proper instrumentation becomes available.

1A. Interstellar Molecules

The research pace in the areas of new molecular detections and molecular formation theories has slowed considerably but progress is continuing in other areas. A good example is the problem of determining the temperatures of complex molecular species in selected interstellar regions. Correct temperatures are vital for abundance determinations and for making accurate predictions for new detections. The temperatures of large molecules (excluding smaller species such as diatomics, triatomics and NH_3) have always been troublesome because few observational data points were available. This situation began to change with the important studies of CH_3SH and HNCS by Linke, Frerking and Thaddeus and of $HCOOCH_3$ by Churchwell and co-workers. Hollis and co-workers have continued to study the temperatures of large molecules using CH_3OH (both ground and torsionally excited states) and CH_3C_2H. An important result found from almost all of these studies is that the rotational temperature is often low and generally always lower than the kinetic temperature of a given species. Whether this is mostly due to subthermal excitation in a particular frequency renge or generally characteristic of the entire ensemble of energy levels in a given molecular species is unknown at present. Table 2, a summary of some of the information currently available, shows the general trend toward agreement for rotational temperatures in Sgr B2 and in the Orion core region.

Table 2 Some representative temperatures for Orion A and Sgr B2

Kinetic T(°K)	Rotational T(°K)	Molecule/Comments	Authors
		Orion A (Core Region)	
150-250		7 vib. ex. HC_3N lines (100-109 GHz) ~ 6" emission region	Goldsmith et al (1982)
	213±60	CH_3OH torsional state ~ 300 K above ground st.	Hollis et al (1982)
	>200	2,2 & 4,4 NH_3 lines at 3.3 km/sec	Wilson, Downes & Bieging (1979)
	150^{+30}_{-10}	8,8 & 9,9 NH_3 lines at 5.5 km/sec	Ziurys et al (1981)
>220		10 NH_3 lines	Morris, Palmer & Zuckerman (1980)
		Orion A (Extended Molecular Cloud)	
	~ 40	1,1 & 2,2 NH_3 lines at 7-10 km/s	Ziurys et al (1981)
	31±9	$HCOOCH_3$	Churchwell et al (1980)
	89±15	CH_3OH ground state	Hollis et al (1982)
121.2±8.2	16.6±1.8	CH_3CN	Hollis (1982)
		Sgr B2 (Molecular Cloud)	
90	10-20	CH_3CN with collisional model	Linke et al (1982)
97±6	18.9	CH_3C_2H	Hollis et al (1981)
	8±4	$HCOOCH_3$	Churchwell et al (1980)
	9±3	CH_3SH	Linke, Frerking & Thaddeus (1979)
175±25		NH_3	Wilson et al.(1982)

Measurements by Snyder and co-workers of the formyl (HCO) in three different transitions in NGC 2024 have indicated a very low rotational temperature - approximately 10K. An important study by Gottlieb, Palmer, Rickard, and Zuckerman showed that many formaldehyde-like molecules are inverted and amplify the background continuum radiation. An important consequence of these results may be that any small interstellar molecule with elements of formaldehyde symmetry may have its temperature determined by the Townes-Cheung collisional pump, which suggests that perhaps the most reliable temperature determinations eventually will come from studies of large molecules which have torsional moments less affected by selective collisions. The relative narrowness of the various temperature ranges in Table 2 suggests that temperatures derived from large molecules are becoming fairly reliable.

It should also be noted that the body of observational literature is large enough now to allow compilation of a first-order catalog of galactic molecular sources and their observed molecular transitions. Normally, new molecular search/detection papers list sources searched for a particular species. More rarely, papers address particular sources and their structure, content, dynamics, etc., by combining perhaps a number of different probes. A proper catalog would compile source by source listings of observed molecular content. For each source, a list of all molecules, all species of each molecule, and all radio frequency transitions of each species, detected in the region, with upper limits given for nondetections, could be compiled. Furthermore, information on the more abundant species, such as CO radiation temperature, extent, column densities, isotope ratios, etc., could be given, along with general structural and dynamical data on the source (coordinates, distance, velocity with respect to the Local Standard of Rest, hydrogen density, kinetic temperature, etc.). Given the large number of sources available, insight into particular regions may be gained through noting similarities with other, better studied regions.

1B. Circumstellar Molecules: Masers and Non-Masers

Masers. The celestial masers which have been studied most thoroughly are those associated with the circumstellar shells of OH-IR stars. Fifteen years ago, Wilson and Barrett reported the first detection of OH maser emission toward late-type stars. Today, considerable progress has been made toward understanding both the maser operation and the physical structure of the sources. OH-IR stars are generally late-type giants or supergiants with well-known optical properties. A significant portion of the total stellar luminosity is emitted at infrared wavelengths, which is interpreted as infrared reemission from a dust shell formed by mass loss from the star. The gas associated with the dust in the circumstellar shell produces the line radiations characteristic of these objects. Maser emission is typically observed in OH, H_2O and SiO. One SiO transition (V=0, J=2-1), is between thermally populated levels and has been used by Reid and Dickinson to confirm the expanding shell model for OH-IR stars.

The carrier of the SiO maser in Orion (IRc 2) has become a famous anomaly because it is either an evolved star in a region of active star formation or it is the only known SiO maser not associated with a late-type star and, hence, it is a unique object in the galaxy. Snyder and co-workers have summarized the arguments suggesting that the carrier of the Orion Sio maser may be an evolved object and Downes and co-workers have shown that there are many arguments suggesting the IRc 2 is a young object. Attempts to detect SiO masers in other galactic regions of star formation have failed and, consequently, Elitzer has constructed a model which may explain the uniqueness of Orion as the only star formation region displaying an SiO maser.

Non-masers. Recent research has suggested that red giant winds may play a more important role in both stellar and interstellar processes than ever before recognized. Knapp and co-workers, have identified a substantisl number of red giants, including both oxygen- and carbon-rich objects, which are thought to have mass loss rates $\gtrsim 10^{-5}\ M_\odot\ yr^{-1}$. These rates are much higher than typically quoted and suggest that, in some cases, mass loss may sharply alter the course of stellar evolution on the asymptotic giant branch. Kwok and others have proposed that red giant winds may actually form some planetary nebulae. <u>Such large mass loss rates also suggest that red giant winds are responsible for an appreciable fraction of the processed stellar material returned to the interstellar medium.</u> Because of the growing realization of the significance of these winds, research into their observable manifestations—thick, circumstellar molecular envelopes—has intensified.

In terms of chemical abundance characteristics, circumstellar objects may be divided into two classes, according to whether carbon or oxygen is most abundant. Among the carbon stars, by far the best-studied is the nearby infrared source IRC +10216. Some 19 molecules have been detected in its envelope via either radio or infrared spectroscopy. Oxygen-rich envelopes apparently have less chemical complexity, and in the solar neighborhood, smaller mass loss rates. The more distant oxygen-rich OH-IR stars have mass loss rates comparable to or even greater than the carbon stars, however. Although a large number of circumstellar sources are now known, little detailed study has been done on circumstellar physics and chemistry in any object except IRC +10216. Since the variations in physical characteristics among objects are unknown, the role of red giant winds in astrophysical processes cannot yet be accurately assessed.

1C. Interstellar Masers. (protostellar masers)

Interstellar H_2O and OH masers are found in regions of active star formation and are considered to be observational indicators for the formation of massive stars. Reid and Moran have recently reviewed the evidence for strong maser activity in regions of high gas density, 10^5-$10^{11}cm^{-3}$. This density is considerably higher than that found in giant molecular clouds. Maser components cluster over a wide range of scale lengths with clusters as small as 10^{14} in diameter reported for W51M. Compact clusters (10^{14}-10^{15}cm) are called centers of activity and are very difficult to explain. Intermediate clusters ($\sim 10^{16}$cm) are believed to be associated with a single star or related clusters of stars while the largest clusters ($< 10^{20}$cm) are associated with different sites of star formation in the same molecular cloud.

1D. Cometary Molecules

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 a 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. The failure to confirm molecular detections reported for some comets (primarily Comet Kohoutek (1973 XII)) in other comets and sometimes in the same comet has added further complications. Because negative results are proliferating with confusing implications, Snyder (1983) has compiled a detailed account of the numerous attempts to detect radio molecular lines in comets, starting with Comet Bennett (1970 II). Most of the reasons for failure have been identified. They include a general dearth of bright comets, lack of telescope sensitivity, poor choices of transitions, poor choices of observing times, and ephemeris errors.

On the brighter side comets are excellent solar system laboratories for studying maser pumping models. We know something about the temperature, velocity and size of a comet as a function of time so, in contrast to the circumstellar/interstellar maser case, we can acquire most of the physical data needed to build meaningful models and interpret intensities. Single antenna observations of cometary OH emission and absorption have made OH the most firmly established radio molecule in comets. The high spectral resolution of radio spectrometers and narrow widths of radio lines allow the cometary OH velocity field to be studied for the first time. Cometary OH pumping models have been constructed which allow radio OH production rates to be determined.

In turn, these production rates have been found to correlate quite well with the visual brightness of the cometary coma and also with optically-determined C_2 and CN production rates. The cometary OH studies are very important for facilitating the identification and study of more complex cometary molecules and hence enlarge our understanding of cometary chemistry.

The gross predictions of OH pumping models have been verified and most future progress will have to come from radio interferometric observations. Recently the potential of interferometric observations of comets was nicely demonstrated when Snyder, Palmer, and Wade used VLA observations of Comet Austin (1982g) to show 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 the high spatial resolution of an interferometer, 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 ultroviolet observations. We expect that careful observational confirmation of cometary maser pumping model predictions will be applicable to furthering our understanding of tne still rather enigmatic galactic masers.

2. OUTSTANDING OBSERVATIONAL QUESTIONS

Here we summarize several of the outstanding observational questions concerning galactic molecules. The discussion is deliberately brief because of the preliminary nature of this draft.

2A. How are galactic molecules formed?

As discussed by W. Langer in a separate draft, small molecule formation often can be explained through ion-molecule formation chemistry. The formation of certain small molecules and molecules larger than formaldehyde probably depends on grain chemistry, shock chemistry, and/or circumstellar mass loss. Many aspects of this problem can be addressed through observations with high spatial resolution of circumstellar shells and dark dust clouds.

The answer to the question of formation is of great interdisciplinary interest because, by volume, interstellar chemistry is the common chemistry of the galaxy.

2B. Are there undetected keystone molecules?

Watson has described HCO^+ as a keystone molecule for ion-molecule reactions. HCO^+ is so important that it has often been said (by P. Thaddeus, I think) that if it didn't exist it would have to be invented for ion-molecule chemistry. The tentative detection of NaOH by Hollis and Rhodes, if confirmed, would provide the first observational evidence in support of oxide grain surface theory (Duley and Millar). Successful detections of metallic compounds beyond NaOH would be important for helping establish grain surface formation mechanisms. In particular, simple molecular species containing atoms of Li, Na, or K versus those containing atoms such as Al, Ca, Cr, Ti, Mn, Mg, Ni, Cu, Fe, Si, or B (which are predicted to be selectively depleted) would help clarify the specific effectiveness of proposed surface formation schemes.

Are the cyanopolyyne ($HC_{2n+1}N$) molecules telling us something about interstellar chemistry just as HCO^+ was? The heavier members of the family are found to exist in two distinctly different environments: a few cold interstellar dark clouds and the warm circumstellar shell of IRC + 10216. In fact, IRC + 10216 has been the most important circumstellar molecular source - the Sgr B2 of circumstellar molecules - it is the only reported source of $HC_{11}N$, the heaviest (147 AMU) and largest ($\sim$15Å) extraterrestrial molecule known. This peculiar behavior of cyanapolyyne molecules suggests that there may be a link between circumstellar shells and cloud chemistry.

Finally, it is important to ask whether there are key molecules associated with progenitor events such as shock chemistry, supernova chemistry, and cloud-cloud collisions.

2C. How are galactic molecules related to star formation?

Very recently, Harris, Townes, Matsakis and Palmer reported Orion ammonia observations with the VLA that revealed two small cloud fragments about 0.05 pc across that rotate rapidly and have masses approximating that of normal stars. These clouds appear to be likely candidates for a stage of cloud development shortly before the formation of low mass protostars. Previously, single dish observations had shown molecular cloud clumping to be fairly common, but these interferometric observations constitute the most convincing evidence to date of the existence of small-scale cloud structure of a few solar masses, rotating at velocities that can stabilize them against collapse.

2D. Is galactic chemistry related to planetary chemistry in any way?

It is hard to ask this question without invoking controversy. Newly formed Comission 51 of the IAU has given this field of research more respectability by listing it as a primary area of interest, "The search for, and study of, biologically relevant interstellar molecules." The previously mentioned VLA results of Harris, Townes, Matsakis and Palmer demonstrate that stars form in a molecular cloud environment which is enriched with ammonia - an important ingredient of the atmosphere in the Miller-Urey hypothesis. Therefore, it is fair to ask whether there may be galactic experiments which could establish connections between interstellar and prebiotic terrestrial chemistry. If there is an advanced chemical evolution in the interstellar clouds and comets, as believed by Hoyle and Wickramasinghe, it should be possible to find some of the larger molecular species generated by Miller-Urey type experiments, such as glycine. My colleagues (Hollis, Lovas, Suenram) and I have conducted extensive searches for conformer I and II glycine in galactic clouds and for conformer I in periodic comets - the postulated H & W carriers of simple life forms. We have calculated that under optimum conditions, the strongest thermal emission signal from glycine in a periodic comet, emitting at 3mm wavelength, would be 10^{-3}f.u. This requires a detection capability which is beyond presently available systems. On the other hand, Dykstra (U. of Illinois) is investigating the oligomerization of HCN because it is possibly the most intriguing route to chemical evolution. A first step may be to form an isomer of $H_2C_2N_2$, such as the HCN dimer, a molecule which has been sought unsuccessfully in the interstellar medium. Other possible $H_2C_2N_2$ isomers which are candidates for being reactants in the production of HCN tetramers include aminocyanocarbene (NH_2C_2N), N-cyanoformimine (CH_2NCN) and five other species. Therefore it should be recognized that there are many possible molecular species which have defined roles in terrestrial prebiological environments and also could be investigated observationally.

2E. What is the true composition of comets?

As described in section 1D, the icy grain halo model does not work. In issue 83-1 of Comet News Service, there is a review of the mounting evidence for the blackness of ice, "... the bastioned Victorian vision of virgin snow white comet nuclei appears to be crumbling. Whipple's "dirty snowball" icy conglomerate nucleus has gotten dirtier and dirtier and it might not even be snowy". Delsemme has pointed out that abundance considerations suggest that comets are likely to be the the most pristine minor bodies in the solar system. They may be of a more pristine nature than even the most primitive chondrites. Ironically, very little is known about the detailed composition of cometary nuclei-a situation that could be greatly changed with the advent of proper millimeter instrumentation.

3. MOLECULAR RESEARCH WITH THE NEXT GENERATION OF MILLIMETER INSTRUMENTATION

Research problems involving categories such as correct cloud temperatures (1A), maser structure (1B, 1C), circumstellar shells (1B), cometary composition (1D, 1E), molecular formation (2A), and star formation (2C) would benefit from a large aperture, high angular resolution, millimeter - wave facility such as the aperture synthesis array discussed by Lada and Bally (16 Jan. 1983 draft). Problems involving weak signals, such as the relationship of galactic chemistry to planetary chemistry (2D) probably would benefit most from a large collecting area, except when cloud clumping is very pronounced. In this case, spatial resolution and high sensitivity would be required. Given the range of problems discussed in this draft, it is clear that the millimeter array would be a very powerful instrument for extending our knowledge of galactic molecular activity.