25 Meter Millimeter Wave Telescope
Memo #78

THE SCIENTIFIC NEED FOR A GOOD SITE FOR THE 25-METER TELESCOPE

21 February 1977

B. Turner

I. INTRODUCTION

In the original scientific justification chapter, the 25-meter telescope was justified in terms of the scientific needs for a) large collecting area; b) high spatial resolution; c) operation at short ($\lambda \lesssim 1$ mm) wavelengths. Since we have fixed the specifications of the telescope, particularly the diameter, it is no longer necessary to discuss item a); that item is fully determined by the mechanical parameters of the telescope. What needs to be emphasized in terms of choice of site, are items b) and c). Item b) of course implies item c) because the highest resolution is achieved at shortest wavelengths. However these items are discussed separately because the particular scientific problems best served are different in general for the two items.

This report is restricted to problems in astrophysical spectroscopy. A parallel report describing continuum aspects will be prepared by others.

II. MILLIMETER-WAVE LINE WORK: THE NEED FOR HIGH SPATIAL RESOLUTION

In this section, we will mostly discuss problems deriving needed resolution from the observation of the J = 3 - 2 transition of CO, at 345 GHz, where the telescope beamwidth is 8''. The predicted aperture efficiency of 15% (implied beam efficiency ~ 20%) is entirely adequate for the problems discussed. Recent work by T. Phillips (BTL) shows that the excess brightness temperature of the 345 GHz CO line is comparable to that of the J = 1 - 0 line at 115 GHz in a wide variety of objects, so that no uncertainty is involved in our projected use of the 345 GHz line. In dealing with molecules other than CO, the implication is carried that they will be observed in their high-frequency transitions ($\lambda \lesssim 1$ mm) so that desired resolution is obtained.

A) EXTERNAL GALAXY PROBLEMS

The recent detection of CO and HCN in external galaxies has raised a large number of intriguing problems and suggestions, the most important of which is that certain aspects of galactic structure may best be understood by high resolution CO studies of external galaxies. CO has been observed in quite different forms from the nuclear regions, on the one hand, and the spiral arm regions, on the other. With present (1') resolutions one can distinguish these different regions for only a few nearby objects.

In the case of the important Seyfert galaxies, distances are so large that even the entire galaxies are underresolved (e.g. NGC1068). With higher resolution one could determine whether the CO emission comes from the very turbulent inner regions (radius $\lesssim 5''$) characterized by broad optical emission lines, or over a more widespread region over which the present beam-smeared observations are also consistent with an average over the narrower optical emission lines that arise in outer regions.

The density-wave picture of galactic spiral arm formation and maintenance will also be served by high resolution studies. In the nearest spiral galaxy, M31, recent observations suggest that CO emission arises along, and possibly on the inner edges of, the spiral arms. With high resolution, this suggestion can be checked, and the question applied to other more distant spiral galaxies. In view of the usual, possibly intractable, problem of locating gas with precision in our own Galaxy vis-a-vis spiral arms, such high resolution studies of CO in external galaxies may well be the only ultimate way to test the density-wave picture, particularly the critical test areas of where shocks (hence compression and molecule production) occur relative to spiral arms.

Of course, high resolution will permit the study of CO in objects beyond the present ~20 Mpc distance limit, set strictly by beam dilution. Thus many more objects than the 8 presently known will be found, and will test our present tentative conclusions that molecular activity in galaxies is correlated with infrared activity, but not with the strength of other attributes, such as non-thermal continuum sources.

Higher resolution will greatly facilitate the study of rotation curves, and of the detailed distribution of molecules. Are molecules concentrated in rings, as in our own Galaxy, and are these rings expanding as a result of bygone nuclear activity? Current models, based on the present low-resolution studies, suggest these aspects and that much will be learned in these areas by more detailed observations of these external galaxies.

Finally, higher resoltuon will facilitate the detection of the weak ^{13}CO species, and answer whether isotope ratios (^{12}C/^{13}C) are the same in external galaxies as in our own. Because the ^{12}C/^{13}C ratio is determined by stellar processing, such studies will have a bearing on questions of cosmological significance, such as whether stellar evolution has pursued similar tracks in very distant galaxies.

B) GALACTIC PROBLEMS

1) The General Problem of Star Formation

Observations of interstellar molecules have, to the present, served one purpose perhaps better than any other: they have indicated the nature of the evolution of large tenuous interstellar clouds through several stages of collapse and fragmentation until stars or star clusters are eventually formed. This is because molecules alone provide a tool for the study of dense, cool, opaque interstellar clouds. Yet, because of limited resoltuion, several tantalizing details of the evolutionary process still elude us. Are interstellar molecular clouds governed in their collapse primarily by rotation, by gravitation, or by turbulence set up by internal energy sources? What is the relationship of the OH and H_2O masers with other non-masering molecules in the cloud? And how do molecules in general, as well as the maser sources, relate to infrared objects and to the very small compact HII regions recently revealed by cm-wavelength interferometry within some giant molecular clouds? What is the nature of the Herbig Ae and Be stellar emission-line objects, thought to be pre-main sequence objects still surrounded by the placental molecular clouds, and the object of intensive study in the infrared and in molecular lines of CO. Intriguing clues about these relationships seem within potential grasp, with resolutions only slightly better than the current 1', but only for the nearby Orion region. Here, mm-wavelength observations have revealed a rapidly rotating disk in the center of which is the Kleinman-Low condensed infrared object; this system has a mass of almost 500 $M_\odot$, very similar to that of the Trapezium stars and their associated HII region. Combined with age estimates of the Orion molecular cloud and star cluster, the picture seems to be a region in which star formation has occurred in bursts every 10^5 years, over a period of 10^7 years; at every burst roughly 500 $M_\odot$ out of a total cloud mass of 10^6 $M_\odot$ forms new stars. These results are the first answer to the age-old question of how interstellar clouds collapse and fragment in forming stars. But we do not know, because of lack of resolution, whether the Orion picture is typical of other regions of star formation in the galaxy. The 6-fold improvement in resolution of the 25-meter telescope at high frequencies will multiply tremendously the number of regions we can study to answer this question.

Higher resolution as well as higher frequency will allow detection of any super-dense regions in molecular clouds. Such regions must exist, since stars are forming in molecular clouds. Thus the final stages of collapse, just before the protostar becomes self-luminous, may be observable with the 25-meter telescope. One particularly interesting hypothesis might be testable, namely that pre-solar nebulae are a major source of interstellar molecules. Even at the small distance of Orion, such a nebula will not be resolved even with the 25-meter telescope, but it should be possible to observe a characteristic distribution of molecular abundances and velocities near these objects if they are actually releasing molecules into the overall molecular cloud.

2) Interstellar Shocks, Compression, and Energetics: Rim Structures, Elephant Trunks, and Globules

Bright rims appear at the interface between dense, neutral regions and diffuse nebulae associated with early-type stars. These rims often outline "comet-tail" or "elephant-trunk" patches of obscuring matter which point like dark fingers toward the sources of ionization. Outstanding examples of such regions already studied with limited resolution in CO are B35, B223, B224, S140, and S264. The study of these interactive regions with high resolution CO observations is important because of the attendant shock waves which induce the formation of CO and other molecules, which represents a heat source for molecular clouds, and which likely trigger instabilities that lead to star formation. Many of these dark clouds and bright rims are located near T-Tauri stars. High resolution studies are needed to decide on the nature of the connection of these stars and recent star formation. Current, low-resolution CO studies also cannot distinguish the possibilities that (a) the heating and compression across the rim is caused by a shock wave preceding the ionization front (rim); and (b) heating and the CO emission ridge is caused by embedded (invisible) stars formed in the shock-compressed gas ahead of the ionization front. High resolution CO observations could reveal localized clumps of heated CO that would indicate the latter hypothesis, and show whether the nearby T-Tauri stars, lying just behind the advancing front, are indeed the earliest manifestations of newly formed stars.

3) Evolved Stars: the Problems of Circumstellar Sheels, Mass Loss, and Evolution (to Planetary Nebulae?)

Many post-main sequence stars, both carbon-rich, and oxygen rich, are surrounded by circumstellar molecular clouds and dust shells. These clouds are all 1' or less in size. This has so far limited detection to about 20 such objects, and permitted a reasonable study of only the closest and largest (IRC10216, size ~30"). One class of problems involves the apparently large mass contained in these shells and how it is maintained in a stable configuration. Higher resolution is needed to establish the density distribution in these objects, and will bear on the question of whether they are releasing molecules into the interstellar medium at significant rates. In turn, information will be obtainable on the classical questions of how much of the interstellar medium has been processed through stars and whether evolved stars play an important role in heating and ionizing the general interstellar medium.

Study of CO emission in a limited number of these objects with dense dust shells has already established whether they are carbon-rich or oxygen-rich, and in the case of the former have, together with limited optical and infrared data, suggested an evolutionary sequence leading to the formation of planetary nebulae. In turn this has led to the suggestion that N-type carbon stars are the principle, if not only, progenitors of planetary nebulae. The intriguing consequences of this idea are that the shells of these objects are more massive than usually assumed from studies of the ionized gas of planetary nebulae, and that the chemical composition differs from what is usually assumed for material returned to the interstellar medium.

Higher resolution will permit the detection of many more of these objects, at greater distances. This is necessary to establish whether carbon stars are progenitors of planetary nebulae, and to determine how the oxygen-rich giants fit in. Higher resolution will also determine whether the density distribution in the molecular shells is consistent with multiple outbursts of mass loss from the star, a possibility presently suggested for IRC10216 but not directly observable yet. Such a result would of course bear on an understanding of the evolution of the giant evolved stars themselves. Finally, higher resolution is needed to determine more accurate isotope ratios in these stars, to get further information about the nuclear processes which are occurring there.

4) Magnetic Fields

Magnetic fields have been measured in many stars, and in interstellar space where its value is typically a few microgauss. Of critical importance to our understanding of the contraction of regions of the interstellar medium into dense clouds and eventually into stars, is what happens to the magnetic fields along the way. Are they frozen into the clouds, thus controlling the geometry and rate of collapse, and determining how fragmentation occurs, or do the fields somehow escape, allowing a much shorter timescale for gravitational collapse?

At present nothing definitive is known about magnetic fields in dense molecular clouds. A few interstellar molecules, among them SO and OH have the potential to solve this problem, by means of their Zeeman splitting. However it is currently difficult to derive from the strongly broadened lines of SO a size for the magnetic field because kinematic effects also broaden the lines. Thus magnetic field values as discrepant as 3 milligauss, and 6 gauss, have been derived in the source Ori A from observations of SO, and OH respectively.

To minimize the effects of kinematic broadening we require a maximum spatial resolution. With high enough resolution, and observation of two or more molecules with different Zeeman splittings, one may in principle solve for both the kinematic component and the magnetic field component of the broadening.

5) The Remarkable Source in Orion A: Pre-Main-Sequence or Post-Main-Sequence?; Dynamis and Fragmentation of a Protostellar Cloud; Is this Source Unique?

Above we discussed in broad outline some aspects of star formation revealed by current observations of Ori A. Many detailed aspects, revealed only partly in Ori A, and not at all in more distant sources because of inadequate resolution, may be fundamental to our understanding of the final stages of star formation. Molecular spectra from the Kleinman-Low/Becklin-Neugebauer infrared sources in Ori A are often characterized by a sharp spike on a broad pedestal. The pedestal is unresolved by current observations. The KL and BN objects are separated by an unresolved 30" and the evolutionary state of both is very uncertain. The pedestal line feature, of width ~30 km/s, is typical of motions arising in *either* pre- or post-main sequence objects. If KL is a cluster of pre-main sequence objects of which BN is the brightest, the large linewidth of the pedestal could be due to collapse, expansion (due to stellar winds), rotation, or turbulence. Observationally there is no way to narrow down the choice without improved resolution. If BN is a highly reddened post-main sequence star that has just left the main sequence, it could be surrounded by a partially ionized, partly molecular fossil Stromgren sphere having the large velocity dispersion characteristic of HII regions. If BN is instead a G, F, or A star that has already passed through a red giant phase, the pedestal emission could be produced by gas ejected from the star.

Very high velocity wings in CO profiles have recently been discovered toward KL/BN, but cannot be assigned with current resolution to either source. If they are associated with KL, then in conjunction with current theoretical models they will determine relatively precisely just where KL is on the way to becoming a pre-solar nebula.

A detailed picture of the relation of the pedestal to the rotating north-south ridge that surrounds KL/BN will tell us much about the dynamics and fragmentation of a protostellar cloud. For example, from current low-resolution data the apparent angular velocity of the dense ridge is of about the right amount to account for the velocity dispersion in the pedestal if the latter is gas from the ridge that has collapsed and conserved its angular momentum, i.e. has not fragmented. If this is confirmed by locating the pedestal more precisely, then it will indicate that fragmentation, of the sort that must have occurred to produce the IR cluster in KL and the many H_2O maser sources, occurs at a later but now rather closely defined stage.

The Ori A region is only 600 pc distant, explaining why we have learned as much as we have even with limited resolution. Somewhat further away is the W3 region (~2 pc) which, like the overall Orion region, seems to contain several different stages of star formation at once. Apparently similar, but even more distant, examples are the DR21 and W51 regions. Perhaps even the largest star formation region in the Galaxy, the giant Sgr B2 complex, will be "resolved" from the dynamic and star formation aspects with resolutions of 8". At present, Ori A is "unique", but several other regions are within range with a 6-fold increase in resolution.

6) The Galactic Center

The very center of the Galaxy (Sgr A "west") consists of a thermal continuum source ~45" in size in the center of which is an intense ($\gtrsim 10^7$ K) small ($\lesssim 0.1"$) continuum source within the inner 1 pc core. Strong IR continuum radiation at 2 μ and 10 μ peaks here, and apparently arises from dust grains heated by massive stars. Structure of size less than a few " is apparent in the IR. Near the center (3' away) is the strange IR and continuum source Sgr A "east" which is though to have been recently ejected from the nucleus.

Several interesting problems can be attacked with arc-sec resolution in CO lines. One is the nature of the peculiar 12.8 μ line of NeII which is significantly redshifted (LSR velocity 75 km/s) and very broad (200 km/s), as observed with 8" resolution. These characteristics imply that events as recent as the last 10^4 yrs have given the inner ionized gas a systemmatic motion with respect to the massive stellar component of material at the Galactic center. At the 345 GHz line of CO, the 25-meter telescope will permit measures of the velocity field of the inner 1 pc to see if the neutral material immediately surrounding the central ionized region shares the intriguing properties shown by the NeII lines, and to allow more precise dynamic and density models of this region to be made. The velocity field near Sgr A "east" can also be measured, possibly resolving the current dilemma of whether this "ejected" nonthermal source lies behind or in front of the nucleus.

7) Detection of Certain New MOlecular Species

Improved resolution will increase the chances of detecting at least two new types of molecular species--those that are likely to be found only in small, dense regions with elevated temperatures (perhaps the final stages of protostellar evolution).

One type of species in this catagory is the highly refractory species containing the as yet undetected atoms P, Mg, Fe; these include PN, HCP, MgO, FeO. These refractory species require high temperatures or other sources of energy to exist in the gas phase. They are thought to have properties similar to SiO and SiS, two refractory species which have been detected only in small, highly energetic regions. In the Orion IR source, observations of SiO appear to reveal the presence of a newly formed star or star cluster which is in the process of volatizing the dust grains in the surrounding gas. Recent theories of the diffuse interstellar bands at 2200 Å suggest that interstellar grains may be made up largely of MgO, FeO, and CaO.

A second catagory of molecules which may be detected in very small dense regions are highly complex species which require high density (and possibly elevated temperatures) to form. This is particularly likely if formation occurs by catalytic reactions on grain surfaces. Key molecular species in this catagory are heavy alcohols and alkanes, ring molecules, and amino acids.

8) Aspects of Interstellar Chemistry

Attempts to test current theories of interstellar molecule formation and destruction in a quantitative rather than qualitative way have so far met with frustration. A prominent reason appears to be inadequate resolution of current observations. Already, our limited data suggests that different species, even such fundamental and chemically similar ones as N_2H^+ and HCO^+, have rather different spatial distributions on the $\lesssim 1'$ scale. In Ori A there is good evidence that the chemical composition of the central KL nebula, of size $\lesssim 30''$, differs from that of the surrounding molecular ridge, of size $\sim 2'$. The reasons may include the higher density and temperature of the KL core, but also the energy input from the embedded IR cluster may be decisive. If, for example, the central protostars are producing gas-phase molecules from the volatization of grains, while molecules are produced by ion-molecule reactions in the surrounding ridge, then great differences in composition are expected. Obviously an attempt to compare in detail observations with formation theories must fail when the observations blend two very different types of chemistry.

More generally, the presence of IR objects and condensed continuum sources within dense molecular clouds is commonplace. The Ori A experience therefore may also be commonplace. To make progress, we must have detailed observations of how the molecular content varies in the vicinity of these objects. Correlations of molecular distributions with gas temperature and density, with extinction, and with the presence of IR radiation, either from heated dust or from condensed objects, is of great interest.

The possibility of observing, at highest resolution (frequency), superdense and ultra-small objects that represent final stages of protostellar collapse, is of interest not only from the star formation point of view, but also to test yet another idea about molecule formation. A long-standing hypothesis is that pre-solar nebulae are a main source of molecules (although the problem of how these molecules disperse throughout giant clouds without freezing out on cooler grains is unanswered). Even at the small distance of Orion, such a pre-solar nebula will not be resolved even at high frequencies with the 25-meter telescope, but it should be possible to observe a characteristic distribution of molecular abundances and velocities near such objects if they are actually releasing molecules into the overall molecular cloud.

Finally, we must understand the excitation and abundance of certain "key" molecules such as N_2H^+, HCO^+, HCN, HNC, and CN all of which have transitions involving rotational levels $J \gtrsim 2$ lying at 270 GHz and higher.

C) THE SOLAR SYSTEM

1) Comets

Much of the line work done on comets in the past 3 years has been controversial, owing to the weakness of the signals, which in turn arises from inadequate resolution. Of concern to mm-wave work appears to be only the nuclear regions of comets; theoretical models show that typical molecules such as HCN should occur only in regions within 10^4 km of the nucleus, thus subtending angles of $\lesssim 20''$. The general chemical composition and physical structure of cometary nuclei is a classical problem dating back to Whipple, who proposed an icy-conglomerate model later modified by Urey, Swings and many others. The nuclear region is intractable to optical work because of obscuration. It is accessible only to the mm-wave region and only with suitable resolution. An understanding of cometary nuclei has important consequences connected with the creation of the planetary system. Kuiper's theory is that comets condensed out of the solar nebula at about the time the outer planets were formed. Certainly a fraction of the gas in the solar nebula neither condensed nor was accreted by planets or comets, but instead was dispersed to interstellar space by radiation pressures. Thus it has been speculated that molecules which constitute the comets (nuclei) may be similar to those found in interstellar space.

Comets also serve as interplanetary space probes. Study of the parent (nuclear) molecules and their relation to the secondary halo species observed optically would provide additional information about the properties of the inner regions of interplanetary space, such as variations in the radiation flux, solar wind, magnetic fields, and the zodiacal cloud.

In summary, information about the detailed chemical and physical structure of cometary nuclei (a) will yield vital data needed in model calculations for the creation of the planetary system; (b) might provide the explanation for the production mechanism of the more complex interstellar molecules; and (c) will make possible the more effective use of data from comet observations in the exploration of the interplanetary medium.

2) Planets

The problems here which require high-resolution mm-wave line observations are limited in number. One recent development is the detection of CO in the atmosphere of Venus and Mars. The linewidths imply a height of $\sim$90 km in the atmosphere of Venus, a region much higher than is accessible by other means. With current resolution the signals are weak, especially for Mars, making the observations as well as the interpretation marginal. With high (8") resolution, not only will the signal-to-noise ratio be greatly increased, but it will be possible to map the CO distribution in the upper atmosphere and hence to study the chemistry and velocity structure of the mesospheric layers. Detailed photochemical models for the upper atmosphere especially of Venus will be testable.

III. MILLIMETER-WAVE LINE WORK: THE NEED FOR SUB-MILLIMETER CAPABILITY

In this section we discuss mostly the problems of detecting important interstellar molecular and atomic species which have no transitions lying at wavelengths longer than the sub-mm ones. What is more, many of these species are expected to occur in physical environs not conducive to the excitation of transitions lying shortward in wavelength of this region. Thus many of these species may never be detectable outside the spectral region discussed here.

The expected low efficiency or even absence of coherence of the 25-meter telescope in the region discussed here is not a problem because the signal strengths are expected to be large (transition probabilities are $\propto \nu^3$) and because the emission regions will be spatially extended ($\gtrsim 1'$). Thus even the $\sim$ 1' circle of confusion estimated for the 25-meter telescope at 350 μ is not a serious restriction for these detection problems.

A) DETECTION OF NEW MOLECULES CONTAINING ONE HEAVY ATOM

A large number of diatomic hydrides, both ionized and neutral, and a few multi-atomic hydrides of astrophysical interest have fundamental frequencies in the wavelength range from 1.2 mm to 350 μ. These species can be observed only at these and possibly at shorter wavelengths. In the following table we list molecules in these categories whose constants are well enough known to estimate quite accurately their fundamental transition wavelengths. These estimates are based on optical spectroscopic data and are accurate typically to 0.1 cm^{-1}, or to 3 GHz. Especially with the advent of a telescope that can search for these molecules, we may expect laboratory work to establish their frequencies much more accurately in the future. Recent theoretical work has demonstrated that marked improvements in the accuracy can be made using existing optical data, but utilizing more sophisticated theory to extrapolate to radio transitions.

In the table, we have limited the list primarily to molecules having fundamental transitions in the 300 μ to 1.2 mm range, since this is the spectral range over which the atmosphere generally allows observations. There are several regions therein for which the atmosphere attenuation exceeds 10 dB. According to calculations by Hall (1967) these regions are roughly 910-934 μ, 770-790 μ, 654-684 μ, 480-583 μ, and 379-418 μ. In the other, window, regions the attenuation at a 13,000 foot site elevation appears not to exceed 6 dB at the zenith, although there are no observational data to verify this. Because the uncertainty in Hall's calculations may be large, we have included in the table several molecules whose transitions lie in the expected opaque regions of the atmosphere; these are denoted with an asterisk.

The highly reactive, as well as simple, nature of the molecules listed in the table suggests that they will be found in interstellar clouds which are considerably more rarefied than those harboring the presently known complex molecules. Because the clouds will be of low density, the molecules in the table may be expected to have low abundances. Nevertheless, detection should be possible because of the very large line strengths which characterize short-mm wavelength transitions. Typically, these larger line strengths can compensate for abundances at least an order of magnitude smaller than the smallest abundances now observed in dense clouds. This puts detectable column densities for simple hydrides at $\sim 10^{12}$ cm^{-2}, which is comparable with theoretical estimates of expected abundances for many hydrides, and with optically determined abundances of CH and CH^+. It will be very important to detect molecules in rarefied interstellar clouds, because the limited chemistry that can occur at low (~100 cm^{-3}) interstellar densities sets the stage for the more complex reactions that follow as clouds contract and become more dense. In this sense, all interstellar molecular chemistry hinges on the precursor reactions that occur in the earliest phases of molecular cloud evolution, phases for which at present there is almost no observational information. The 25-meter telescope, at a good site, will provide such data.

Because of the high spectral resolution of radio mreasurements here, observations of light species will provide a reliable standard for comparison with optical data. In particular, accurate radio measurements of doppler linewidths will aid the interpretation of many highly saturated ions (e.g. C^+) observed in the ultraviolet. The strengths of MgH and AlH relative to those of their ions will be sensitive indicators of the ultraviolet and optical fluxes reaching the interiors of medium or dense clouds.

B) DETECTION OF NEW HEAVY MOLECULES IN DENSE REGIONS

MOlecules containing more than one non-hydrogen atom usually have fundamental frequencies at 2-mm wavelength and longer. Therefore they do not in principle represent an area of research requiring the highest frequency range of the 25-meter telescope. However, the combination of high frequency and high resolution capability of the telescope may allow the detection of some heavy molecules that would not otherwise be possible. If the molecules have very small abundances, they may be detectable only by observing the highest-frequency transitions, because these have the largest line strengths. In turn, these transitions, which require relatively high densities to be excited, may emit only from very small, high-density regions within the cloud, and hence require high spatial resolution. Alternatively, high temperatures or other energy'sources may be required to excite the high-frequency transitions of these species, and these phenomena would also be restricted to small regions. Of particular interest are small regions wherein interstellar grains appear to be broken up by newly formed massive stars. One such region may exist in the case of the Orion Nebula. Highly refractory molecules such as SiC, MgO, FeO, PN, and heavy silicates, may occur and be observable in the gas phase only in such special regions as these. Detection of such species, so far unachieved, will provide essential clues about the composition of interstellar grains, a subject that has intrigued and defied astronomers for half a century.

C) EXCITATION STUDIES OF "KEY" INTERSTELLAR MOLECULES

Certain molecular species are fundamental to current theories of interstellar molecular chemistry involving gas phase reactions. These species are N_2H^+, HCO^+, HCN, HNC, CN, and C_2H. All of these species, containing only two heavy atoms, are relatively light and hence only their fundamental ($J = 1 - 0$) transitions lie at currently accessible regions of the spectrum. To understand the excitation, hence abundances, of interstellar molecules requires data for at least the lowest 3 transitions, and very preferably more. The third and fourth transitons up for the above species lie at ~270 and 360 GHz respectively. The species C_2H has not even been measured in the laboratory yet--its identification currently rests on theoretical calculation. Observations of its transitions at higher frequencies are needed even to secure its identity.

As mentioned earlier, attempts at a quantitative understanding of interstellar chemistry have proved frustrating so far. Operating at sub-mm wavelengths, the 25-meter telescope can attack both of the problems currently felt to be at the root of the dilemma--inadequate spatial resolution to relate each molecular species adequately with the surrounding physical conditions and with each other, and inadequate understanding of the molecular abundances owing to lack of observations of higher transitions.

Besides the "key" molecules, it will be important to observe all of the remaining interstellar molecules at wavelengths shorter than 2 mm. Although the majority of these species have been observed in more than one transition at longer wavelengths, the most sensitive determinations of temperature and density in interstellar clouds will come from observations of their most highly excited transitions, where the molecular populations are decreasing. These transitions typically lie at 2 mm wavelength and shorter.

D) OBSERVATIONS OF RESONANT ATOMIC TRANSITIONS: THE PROBLEM OF CARBON

Among astrophysically abundant atoms, neutral carbon has two highly important ground-state resonant transitions which are potentially accessible with the 25-meter telescope. These are the 2p ($^3P_1 \rightarrow {}^3P_0$) and 2p ($^3P_2 \rightarrow {}^3P_1$) transitions at 0.609 and 0.369 mm, respectively. In low-density clouds, where atomic carbon can be observed optically, it is always singly ionized. Only in dense molecular clouds is atomic carbon in neutral form, and it is observable only in these two sub-mm transitions. Observations of CI are vital for a number of reasons. They will resolve the present controversy over the fraction of available carbon tied up in CO (the answer to this question is of central importance in current theories of molecule formation). The relative distributions of CI and carbon-containing molecules will also provide major clues about molecule formation mechanisms. It will also be possible to determine whether CI is abundant enough to compete with CO as an important cooling mechanism for dense interstellar clouds. Maps of CI emission will serve to locate embedded and otherwise invisible hot stars (near which the CI will become CII) which have not yet formed compact HII regions but which may promote molecule formation. The distribution of CI as a function of distance into a cloud will provide information about the UV radiation field in which the cloud is immersed. Because of the presence of nearby often invisible stars, the UV field is different for every cloud, yet the details of the UV field are important in determining the evolution and chemical composition of these clouds. As yet, no observational method exists to examine these fields. Maps of the CI distribution will also provide tests of theories of the carbon ionization equilibrium as a function of depth into the clouds.

E) HIGH-FREQUENCY HYDROGEN RECOMBINATION LINES

For a given temperature and density, a cloud of ionized hydrogen produces a recombination line-to-continuum emission intensity ratio which is peaked at a determined frequency, decreasing at lower frequencies because of decreasing stimulated emission of the line, and decreasing at higher frequencies because of decreasing optical depth in the lines. The cooler or denser the ionized region, the higher the frequency at which the line-to-continuum ratio peaks. Until about 1972, recombination lines were observed only to wavelengths as short as 1 cm; these observations were sensitive only to "standard" HII regions of temperature about 10,000 K and densities of about $10^{3.5}$ cm^{-3}. Such regions were already recognized by optical observations. More recently, recombination lines have been observed to 3 mm wavelength and reveal the presence of denser, cooler HII regions imbedded in the hotter, more tenuous regions. In the Orion Nebula, this cooler region is at 7000 K, has a density of $10^{4.5}$ cm^{-3} and a size of only 0.04 pc. Yet smaller, denser, and cooler regions must exist, for example, in the core of the Kleinman-Low infrared object where a cluster of new stars seems to have formed. At 1 mm wavelength, the line-to-continuum peak would correspond to HII components at 5000 K, with densities of 10^6 cm^{-3} and sizes of only 0.001 pc. Such objects would correspond with the very earliest self-luminous phases of a star. Their observations would test current pictures of "pre-solar nebulae", and the effects of still-infalling material on the formations of an HII region around the newly formed star.

III. CONCLUSIONS

Any look forward in a rapidly advancing subject such as mm-wave astrophysical spectroscopy is always colored by the most recent discoveries. However, the past two years have seen developments, both at longer mm-wavelengths and in the infrared, that focus attention even more firmly toward the sub-mm region as being the most fruitful for progress in a wide variety of fields, ranging on the one hand from the structure of external galaxies, the chemistry, dynamics and structure of the Galactic interstellar medium, and the problems of star formation; on the other hand to the more local problems of planetary atmospheres and the nature of comets.

In the past few years there has been an increasing overlap in the astrophysical problems best studied through mm-wave radio astronomy on the one hand, and infrared on the other. In the area of spectroscopy, as opposed to continuum, a complete merging of the disciplines to solve specific problems has yet to occur but is inevitable. Infrared spectroscopists have pushed upward in wavelength to the 100 μ range, and recent developments in heterodyning techniques (using photodiode oscillators and detectors) promises shortly to reach the 350 μ window, already attained by continuum workers. Several important interstellar molecular and atomic lines have been detected at infrared wavelengths (the acetylene molecule at ~14 μ; the H_2 molecule at 28 μ, lines of [OIII] and [SIII] at 88 and 18 μ) as well as several solid-state features which are indicating the nature of interstellar grains (silicate features at 33 μ, $MgCO_3$ features at 11 μ, ices at 3.1 μ, and bending mode resonances of SiO_2 at 18.5 μ). In the solar system, infrared transitions of phosgene (PH_3), of CO_2 and of ammonia have been detected in the atmosphere of Jupiter, and will obviously soon be applied to the interstellar medium.

This strong push by infrared workers toward longer wavelengths should be met by an equally vigorous push by radio astronomers to shorter wavelengths. A merging of these disciplines already seems feasible in the area of detectors, given the promising progress in bulk infrared detectors, both incoherent and coherent (using dye-laser pumps) and in the technology of Josephson junctions, which can operate at mm or infrared wavelengths. It is in the area of telescopes that the infrared and radio sciences presently are further apart. The 200-inch (5.1-meter) Palomar telescope is at an inadequate site for far-IR work. The largest current sub-mm telescope at a good site or balloon-borne is the 88-inch (2.2-meter) for Mauna Kea. The proposed U.K. infrared telescope (3.8-meters) for Mauna Kea is too small for wavelengths $\gtrsim 0.8$ mm and operates incoherently at 300 μ. The speculative U.K. 14-meter telescope would indeed fill the gap adequately between 1 mm and 350 μ, if it is ever built, and <u>if</u> it is placed on an adequate site, but this latter condition presently seems very unlikely.

The 25-meter telescope, operating coherently to $\lesssim 800$ μ and incoherently to shorter wavelengths, has the accuracy to make great advances at short mm and long infrared wavelengths. The 25-meter telescope, operating coherently, will be 6.1 times more sensitive than the best existing telescope at 0.8 mm. Placed at a favorable site, the 25-meter telescope will be versatile enough to meet the future challenges which will arise as astronomy grows and changes.