MILLIMETER ARRAY
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Molecular Clouds

The working group on molecular clouds identified many scientific problems which can be uniquely addressed by the millimeter array. Most of these are related to a central theme: understanding the processes which precede and accompany the formation of stars and planetary systems. While other instruments (both existing and planned) will make important contributions on this theme, the MMA appears to provide the combination of sensitivity, spatial resolution, and spectral resolution which is best suited to this problem.

Understanding star formation begins with understanding the structure of a molecular cloud before stars form. The simplest scenario, in which a cloud simply collapses to form a star, does not seem realistic in general. Instead the velocity field of molecular clouds is dominated by supersonic turbulence, the source of which is not clear. Thus we are led to our first scientific problem: <u>to characterize the turbulent structure of molecular clouds</u>. A powerful probe of turbulence is a study of velocity fields as a function of scale size. For example, do they follow a Kolmogorov spectrum? Existing studies cover only about one order of magnitude in size. The MMA provides a unique capability to provide information over a much larger range of scales. Experiment #1 outlines a plan for studying the turbulent velocity field on scales ranging from 3" to 1° (0.008 pc to 9 pc at 500 pc). While the upper end of this range could be done on existing instruments, using the mosaicing capabilities of the MMA allows coverage of this 3 order of magnitude range in a single experiment. The observing speed of the MMA will allow this experiment to be done on several clouds with different properties (<u>e.g.</u> those forming high mass stars, those forming low mass stars, quiescent clouds, Bok globules). More importantly, the present data indicate that linewidths decrease with decreasing scale size, so that the transition to subsonic turbulence can be explored only with the MMA's capability for high spatial resolution. An interesting aspect of this experiment is that the relevant plane for the problem is not the map plane but the spatial frequency plane which is naturally provided by

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an array. The spectral lines that seem most suited to this project are the ^{13}CO and $C^{18}O$ J=2→1 lines. For denser regions, the CS lines (e.g. J=2→1 or 3→2) may be desirable in order to select shorter line of sight distances.

In pursuing the turbulent structure to smaller scales, one hopes to begin isolating individual turbulent elements (fragments) which could eventually become individual stars. In particular, the distribution of angular momentum on small scales can be studied. The second scientific problem is to identify and characterize "protostellar" fragments. By protostellar, we mean that no luminous condensed object (a main-sequence star or pre-main-sequence star) has formed. Since the gravitational energy released by contraction is effectively radiated away during the phases we wish to study here, we assume that the temperature remains low. These objects are in the natural domain of the MMA. We find (see Expt. #2) that the best way to identify these fragments is through their dust emission at short wavelengths. As long as the dust temperature does not drop too low, the brightness temperature will be proportional to the dust temperature and the column density. Then, in the absence of temperature gradients induced by internal sources, the interferometer will respond primarily to enhancements in the column density which occur as a fragment contracts. Since the opacity of the dust is so low at 1mm, it will remain a good tracer of column density up to $N = 4 \times 10^{25}$ cm^{-2}. A 1 $M_{\odot}$ protostar in spherical collapse would reach an average column density sufficient to make $\tau_{1mm} \sim 1$ only at radii approaching 165 A.U. (~1" at the distance of nearest clouds).

Having identified candiate protostellar condensations, we would want to characterize their kinematic and physical parameters. For kinematic studies, (see Expt. #3) any spectral line would work, so one would choose CO 2→1 for maximum sensitivity, once again using the interferometer to resolve out the confusing ambient cloud. If opacity in the surrounding cloud distorts the emission from the fragment, lines of lower opacity or higher characteristic density could be used to discriminate against the emission from the ambient cloud. As the fragment shrinks, these lines will become comparable in brightness to the CO emission from the fragment. Convincing evidence that a fragment is truly protostellar will require the kinematic signature of collapse, probably combined with rotation. For this purpose, high spectral and spatial resolution is required in order to map the line centroid and shape across the object. The ordered motions of collapse and rotation are small at early stages and will only emerge from the turbulent velocity field when the object is quite small. The free fall velocity reaches 3 km s^{-1} when a 1 $M_{\odot}$ protostar reaches a radius of 140 A.U. (1" at the distance of the nearest clouds). Consequently, only the high spatial resolution of the MMA will be capable of mapping the velocity field in these objects.

Determination of the physical properties (temperature, density, ionization state, and chemical abundances) is also necessary for testing models of protostellar collapse. In particular, one wants to map these properties across the object. The same probes (see Expt. #4) that have been used in extended clouds (CO for temperature, rarer CO isotopes for column density, high dipole species like CS for density) could be used on the protostellar fragments until the fragment density becomes so great that these probes become optically thick or thermalized. Once these probes fail, only the dust continuum will remain as a column density probe. For determining the density, multiple transitions of a single molecule are required (e.g. Snell et al. 1984); the ability to observe simultaneously in several frequency bands would be very useful for this project (see Expt. #4).

Do we now have any evidence that such protostellar condensations exist? The answer is yes. The IRAS survey has found hundreds of sources in nearby clouds, generally embedded in dense clumps of gas, which have no optical counterpart. Those with very low 60-100 μm color temperatures are likely to be the youngest objects. Notable among these sources is the isolated globule B335. Observations with arcsecond resolution of objects like B335 would be able to determine the structure very near the forming star, discriminating between disks and proto-binary stars.

Special opportunities exist in regions when massive stars have already formed since these stars will warm their surroundings enough that many molecular transitions will be excited in nearby, still proto-stellar, condensations. For example the warm (T_k = 30-50K) cores of S140, M17, and NGC2024 clouds appear to have regions of very high density (n ~ 10^6 cm^{-3}). This dense material is probably clumped and preliminary results from the VLA and mm interferometers suggest clump sizes of 5-10 x 10^3 A.U. with masses in the range 0.5 to 5 $M_\odot$, in the range expected for protostellar condensations. A still more extreme example of these regions is the Orion "hot core." The brightness of this source in many spectral lines has allowed detailed study with existing arrays, and these form a paradigm for what would become possible with the MMA. However, the presence of massive stars and protostars in the vicinity of the hot core may have distorted its properties. Observations of less evolved regions are therefore desirable.

Another interesting possibility is to make absorption line measurements against background H II regions or dust emission regions (see Expt. #5). The velocity in these absorption features would allow discrimination between infall and outflow on scales very close to those of the forming object.

There is growing evidence that disks are common features around young stars although most of the evidence so far is circumstantial. For an understanding of star and planet formation we would like to know when such disks form and to study their kinematic and physical properties. Thus we are led to the scientific problem of identifying and characterizing disks around young stars. A related phenomenon is that of high velocity, often bipolar, outflows from young stars. The disks are often invoked to channel the flows into the bipolar form which is often seen. In other models, the disk itself is the source of the outflow. Magnetic fields may play an important role in driving or channeling the outflows. In turn the outflows may have a major impact on subsequent star formation by disrupting surrounding material, sweeping up dense shells, compressing pre-existing clumps, or by regenerating the general turbulent field in the cloud.

Addressing first the nature of the outflowing material seen as broad wings on CO lines, we note that several arguments suggest that the outflowing matter is strongly clumped. Resolution of the clumps would be possible with the MMA. It seems clear that the matter seen in the broad CO wings is generally swept-up matter from the ambient cloud. The stellar (or disk) wind is presumably faster, less massive, and at least partially ionized, as reflected by the detection of infrared recombination lines or radio continuum emission from many of the stars driving outflows. Study of these winds would become possible with the MMA. Many winds appear to be quite optically thick at radio wavelengths, so observations of the free-free emission at millimeter wavelengths may be more effective. Also the recombination lines (e.g. H39α or H40α near 2.6 mm) may be strong enough to detect, providing velocity information on the ionized component (see Expt. #6). If part of the wind is neutral and molecular, very broad ($\Delta V \sim 300$-1000 km s^{-1}) wings may appear on the CO profiles. Such wide lines, while consistent with many models, would rule out some disk-driven wind models.

One of the few disks studied in detail so far is that in the Orion hot core (Wright and Vogel 1985; Masson 1985). Using the Wright and Vogel (1985) estimate that dust opacity varies as $\lambda^{-1.3}$, assuming the gas density is proportional to n^{-2} and adopting the Keene, Hildebrand and Whitcomb relation, $N(HI + H_2) = 1.2 \times 10^{25}\, \tau_{0.4mm}$, Wootten has calculated the source structure as a function of frequency, and finds

$$T_b\,(r.\lambda) = 1448\, \lambda^{-1}(\mu m)/r^{-1}(pc)\ K.$$

Measurements of the chemical structure of these disks can also be made if several species are observed. A recent interferometric study of Orion (Vogel 1985) has shown that since different molecular species are differently distributed, the physical conditions must vary across the source. If observations with the MMA are made in a double sideband mode and if a 1.5 GHz IF is available, the sidebands can be placed so that one is at 259 and the other at 262 GHz. Synthesis of as many as 15 lines, probing different conditions, can then be carried out. Among them are $H^{13}CN$, which can be compared with $H^{12}CN$, several hyperfine components of C_2H, which generally avoids hot cores and so traces the ambient gas, SO, which is found in turbulent outflow regions, two lines of SO_2, which probes hot outflows, HDCO, and dimethyl ether. The baselines and velocity resolutions required would be similar to those employed in the previous experiment.

Perhaps one of the most intriguing questions which can be addressed with the MMA is that of the magnetic structure of the dense cores at the centers of the outflow sources. During the time it will take to map out disks in HCN as described above, continuum observations in two polarizations can be carried out in the other sideband with sufficient sensitivity to measure polarizations of 1-2%. If the dust grains in the disk are elongated, and aligned by the magnetic field, these observations should indicate the direction of the field in the disk and cloud core. It will then be possible to study whether field and polarization alignments become more ordered in denser regions and whether there is any overall relation between the directions of the high velocity outflows and of the magnetic fields. By differencing the left and right circularly polarized parts for the line emission of such a molecule as SO and mesuring the frequency shift, the magnitude of the magnetic field can be mapped so that is should be possible trace the variation of field strength and compare it to density morphology. In addition to the dual polarization capabilities, spectral resolution of at most a few times 10 kHz will be necessary for this project, as well as sensitive continuum and line performance at ~ 1mm.

As a result of improved infrared detection techniques, in particular speckle interferometry, it has been shown that in a number of cases the dust around low mass stars is distributed in a disk (Beckwith et al. 1984; Grasdalen et al. 1984). The sizes of these disks are usually a few hundred A.U., that is, comparable to the pre-planetary solar system (cf. Aumann et al. 1984). However, the infrared observations provide only indirect measurements of the disk mass and no velocity information. Initial 7" resolution observations of the HL Tau disk with the OVRO interferometer failed to resolve the CO source but a lower limit of ~ 10^{-3} $M_{\odot}$ was obtained, comparable with the mass of the pre-planetary solar system.

For HL Tau, the peak flux in the J=1-0 CO line was ~4 Jy and the 2.7 mm continuum flux was 100 mJy. The sensitivity and resolution of the MMA should permit the routine detection of such objects. For example, with a 1 km baseline, the resolution of J=2-1 CO, 1.3 mm, is 0".25. At 160 pc, the Taurus cloud distance, this corresponds to 40 A.U. Thus it will be possible to compare the speckle infrared dust measurements (~ 0".3 resolution) directly with the gas properties, since an 8 hr. integration should lead to a map with SNR (signal to noise ratio) 10. It will also be possible to sample the velocity structure much closer to the star and determine if we are observing gas in Keplerian orbits. Adopting a typical stellar mass of 1 $M_{\odot}$, the velocity at 0".13 radius and 160 pc distance should be ~ 6 km s^{-1}. With 20 kHz filters, the velocity resolution will be 0.05 km s^{-1} and velocity gradients will be readily discernible. Extrapolating from the HL Tau case, it should be possible to observe a reasonable statistical sample of such objects and ascertain their properties. In particular, it may be possible from the velocity information to ascertain which are likely to be protoplanetary disks and which are incipient binary systems. Numerous T Tauri stars and related objects are obvious candidates for such studies. In addition, it may be possible to make at least continuum measurements at 1.3 mm of the disks around the closer disk-like structures around β Pic, Vega and Fomalhout and further investigate their nature.

We note that the great sensitivity of the array will make possible the detection of many of the objects discussed above throughout our galaxy. Thus one can imagine a class of projects involving galactic structure. Thus one could use the MMA to <u>identify protostellar clumps, bipolar outflows, or disks throughout our galaxy</u> (see Expt. #7). These would serve first as test points for galactic kinematic studies. Since the interferometer would resolve out most of the extended emission along the line of sight, revealing only the compact structures, some of the confusion in current CO surveys could be alleviated. In a similar way SiO masers could be used to trace the velocity field in the galactic bulge, addressing questions of bulge rotation and velocity dispersion. The star formation rate could be studied as a function of galactocentric radias (R_{GC}) using the MMA to count protostellar cores and bipolar outflows. With sufficient statistics, one could also use the observed M_{CO} vs M_* relations (Levreault 1985) to investigate the initial mass function and its variation with R_{GC}.

Of particular interest to galactic structure studies will be the investigation of the inner regions of our galaxy, particularly the inner several hundred parsecs, where gamma ray observations (Blitz et al. 1985) suggest that the usual relation between CO luminosity and mass breaks down. The nature of the gas and of star formation in this region are vital to efforts to understand nuclear starbursts in other galaxies. Again, protostellar fragments or bipolar outflows could be used to probe the velocity field, thus constraining the gravitational potential and mass distribution as well as the star formation activity in this region.

The MMA would also prove a valuable probe of the inner 3 pc of the galaxy where many fascinating phenomena have been found. The MMA array can probe the major components in this region (ionized gas, neutral molecular gas, and dust). For this work, one would like 0".1 resolution. Finally, a more speculative possibility is to study the accretion disk around the black hole. Maps with very high angular resolution of the H and He recombination lines could push the studies of rotational velocities much closer to the center than possible with infrared techniques, constraining the mass of the central object. In addition hyperfine lines (analogous to the 21 cm line but at mm-wavelengths) may be produced from H-like ions of heavy elements (the Sunyaev Curasov effect) in the very hot gas of the accretion disk.

References

Aumann, H. H., Gillett, F. C., Beichman, C. A., de Jong, T., Houck, J. R., Low, F. T., Neugebauer, G., Walker, R. G., and Wesselius, P. R., *Ap. J. (Letters)*, **278**, L23.

Beckwith, S., Zuckerman, B., Skrutskie, M. F., and Dyck, H. M. 1984, *Ap. J.*, **287**, 793.

Blitz, L., Bloemen, J. B. G. M., Hermsen, W., and Bania, T. M. 1985, *Astr. Ap.*, , 267

Grasdalen, G. L., Strom, S. E., Strom, K. M., Capps, R. W., Thompson, D., and Castelaz, M. 1984, *Ap. J. (Letters)*, **283**, L57.

Keene, J., Hildebrand, R. H., and Whitcomb, S. E. 1982, *Ap. J. (Letters)*, **252**, L11.

Levreault, R. M. 1985, Ph.D. thesis, The University of Texas at Austin.

Masson, C. R. 1985, private communication.

Snell, R. L., Mundy, L. G., Goldsmith, P. F., Evans, N. J. II, and Erickson, N. R. 1984, *Ap. J.*, **276**, 625.

Vogel, S. N. 1985, private communication.

Wright, M. C. H., and Vogel, S. N. 1985, preprint.

Experiment #1: Characterize the Turbulent Structure of Molecular Clouds

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Purpose:

1. Determine turbulent velocity spectrum over 3 orders of magnitude in spatial scale (0.01 to 10 pc at a 500 pc distance).

   Investigate the energy cascade from large turbulent cells within a cloud to the smaller cells (i.e., does the turbulence follow a Kolmorgorov type of spectrum)

2. Determine when supersonic line widths are important. Determine what is the source of the line widths (e.g., what role do magnetic fields play in supporting clouds, when and how do the young stars affect the line widths throughout the cloud).

3. Investigate what are the differences between active, high mass star-forming regions and non-flamboyant regions and why they differ.

Observations:

1. Smallest scales (3" - 30")

   Instrument: 90-m array in a circular-random configuration.
   Tsys = 500 K
   Spectral line
   Freq. = 13CO (J = 2 - 1) transition
   (simultaneous observations of other lines could be beneficial. For the denser regions C180 and 13CO observations may be needed.)
   Spectral resolution = 125 kHz (0.17 km/s)
   Bandwidth = 256 channels would be sufficient
   Field size = 30":

   Object: A few (4?) molecular clouds within 1 kpc of the Sun (Orion, Taurus, Rho Ophiuchus, for example) which represent difference classes of clouds and a representative Bok globule.

   Project: Map 6 fields in each cloud to a rms noise of 0.1 K.
   Int. Time = 6 hours per field.
   Fields chosen at random within a 1 square degree sub-section of the cloud.
   4 clouds observed each day. Total of 6 days needed for this phase of project.
   Bok globule requires an additional day.

   Why this instrument: Only instrument capable of reaching the small scale structures in a reasonable amount of time.

2. Intermediate scales (10" - 90")

Instrument: Multi-telescope array.
Tsys = 500 K
Spectral line
Freq = 13CO (J = 2 - 1) transition
(simultaneous observations of other lines could be beneficial. For the denser regions C18O and 13CO observations may be needed.)
Spectral resolution = 125 kHz (0.17 km/s)
Bandwidth = 256 channels would be sufficient
Field size = 90"

Object: Same objects as above.

Project: Map 24 fields in each cloud to a rms noise of 0.1 K.
Bok globule could be done with fewer fields since globules are much smaller than clouds.
Int. Time = 1.5 hours per field.
4 fields surrounding each of the fields mapped with the 90-m
Total of 6 days needed for this phase of project.

Why this instrument? While comparable to the resolution of present day instruments (e.g., Nobeyama if it could reach this frequency and if it had the same receiver, atmosphere, etc.), the proposed instrument is 80 times faster.

3. Large scales (45" - 1 deg)

Instrument: 4-m dishes used like a single-dish telescope (i.e., phase information is not needed)
Tsys = 500 K
Spectral line
Freq. = 13CO (J = 2 - 1) transition
(simultaneous observations of other lines could be beneficial. For the denser regions C18O and 13CO observations may be needed.)
Spectral resolution = 125 kHz (0.17 km/s)
Bandwidth = 256 channels would be sufficient

Object: Same as above.

Project: Sample 100 positions per cloud chosen so as to sample as wide a range in spatial scales as possible.
Map each position to a rms noise of 0.1 K.
Int. Time = 1 min per position
4 clouds observed each day. Total of a few hours needed.

Why this instrument: Faster than any single dish telescope by a factor of 5 (i.e., square root of the number of individual dishes). Common calibration, etc. with other phases of the project.

Data Reduction: Data used in the u-v plane only; no conversion to maps needed. Reduction of data does not require a large computer and probably will be simpler than is typical for the VLA.

Experiment #2: Identify Protostellar Fragments

The MMA will be intrinsically more sensitive to continuum emission than to line emission because of the larger bandwidth. For a 1% bandwidth in continuum observations (e.g., 1GHz at 100 GHz) compared to a 1 km s^{-1} wide line, the signal to noise will be the same for a line which is 55 times stronger than the continuum. For example, if dust and gas temperatures are equal and if one observes a thermalized, optically thin line (e.g. ^{13}CO or $C^{18}O$), then an optical depth of dust which is 55 times smaller is equally detectable. If $T_D > T_K$, if one compares to a non-thermalized or a thick line, or if larger continuum bandwidths are achievable, the advantage of continuum observations increases. Since the opacity of the dust rises steeply with frequency, the advantage of dust emission also grows rapidly with frequency. Consequently, we have conducted our thought experiment to detect protostellar fragments in the continuum at 1 mm.

We assume

$$\tau_{1mm} = 2.5 \times 10^{-26} N_{tot}$$

$$T_D = 20 \text{ K}$$

so $T_B = 5 \times 10^{-25} N_{tot}$

and we compute a minimum central N_{tot} by assuming the protostar is spread uniformly through a sphere of radius r(A.U.). Then $\langle N \rangle = 1.1 \times 10^{30} \frac{M(M_\odot)}{r^2(\text{A.U.})}$.

so $\tau_{1mm} = 1$ at r = 165 A.U. for a 1 $M_\odot$ protostar.

To calculate what we could detect, we use the basic equation given by Hjellming

$$\Delta T_b = \frac{0.64 \text{ K } (Tsys/100)\,[B_{km}/D/10]^2}{f_{geom}\,[\Delta t_{min}\,\Delta\nu_{GHz}\,(N_B/210)(n_a/n_M)]^{1/2}}$$

and set Tsys = 500 K, D = 10, $f_{geom} = 1$, $\Delta\nu_{GHz} = 1$, $N_B = 210$, $n_a = n_m$, to get

$$\Delta T_b = \frac{3.2\,B_{KM}^2}{(\Delta t_{min})^{1/2}}$$

or setting $B_{KM} = \frac{0.''2\,\lambda(mm)}{\theta}$ where θ is the desired resolution in arc seconds.

Then for a 3σdetection, we need

$$T_b\,(3\sigma) = \frac{0.38\ \lambda^2(\text{mm})}{\theta^2\ (\Delta t_{min})^{1/2}}$$

For a canonical 8 hour day's worth of integration, we obtain

$$T_b\,(3\sigma) = 17\ \text{mK}$$

for $\lambda = 1$ mm and $\theta = 1''$.

For $T_D = 20$ K, this means we need $\tau_{1\ mm} = 8.7 \times 10^{-4}$ or $N_{tot} = 1.7 \times 10^{21}\ cm^{-2}$.

This column density would be reached by our putative 1 $M_\odot$ protostar at 2.5×10^4 A.U. This would imply that such an object could be detected, but not resolved, at 25 kpc. More nearby objects could be resolved and studied in detail.

Experiment #3 Kinematic Studies of Protostellar Fragments

We chose to do the kinematic studies in the CO 2 $\rightarrow$ lines. To obtain detailed kinematic information, we want a velocity resolution of 0.2 km s^{-1} and a spatial resolution of 0."2. This would require baselines of 1.3 km for the J = 2 $\rightarrow$ 1 line of CO.The basic sensitivity equation presented in Experiment #2 becomes

$$\Delta T_b\,(1\sigma) = \frac{5.2\text{ K }\ (0.''2/\theta)^2}{[\Delta t(\text{days})(\nu/230)\Delta v(\text{km s}^{-1})]^{1/2}}$$

↳ 8hr "days"

For a 20 K line, 1 day of integration would achieve good signal to noise with $\Delta v = 0.2$ km s^{-1}.

Experiment #4 Determine the Physical Conditions in Protostellar Fragments

a. To determine the column density distribution across the fragment, one would use molecular lines with $\tau \lesssim 1$. As the fragment contracts, many lines will become thick, so one would move to rarer isotopes. If $T_K = 20$ K, one would like to use lines with $T_R <$ 10 K to avoid saturation. The calculation for experiment #3 then suggests integration times of several days or a relaxation of the velocity resolution. At higher column densities, the dust continuum would be the only probe of column density.

Modifying the calculation of experiment #2 to achieve 0."2 resolution raises the $T_b(3\sigma)$ to 0.43 K and the required N_{tot} to 4.3 x 10^{22} cm^{-2}. Since the dust does not reach τ = 1 until $N_{tot} = 4 \times 10^{25}$ cm^{-2}, we have a column density probe which can work over 3 orders of magfnitude to study the distribution over the fragment.

b. To determine the volume density, ionization state and chemical abundances require a multiline study combined with a better theoretical underpinning than currently exists. Observations of many lines will clearly be critical. Flexible spectrometers and the capability to observe in several bands simultaneously will certainly be helpful. For a specific calculation, we consider the CS $2 \rightarrow 1, 3 \rightarrow 2, 5 \rightarrow 4$, and $6 \rightarrow 5$ lines. These have been observed in several dense regions and used to infer the presence of $n \sim 10^6$ cm^{-3} and to suggest the presence of the clumps we are now discussing. To observe the higher lines of this series, one needs relatively warm regions (T_K = 30 - 50 K). We suppose that the lines observed by Snell et al. (T_R^* = 1 - 8 K) do not increase in brightness with decreasing beam size to obtain a worst case sensitivity requirement. The most critical CS lines for constraining the highest densities are the higher J transitions at 245 and 294 GHz. Thus site quality is an important consideration. If we take T_{sys} = 500, we use the equations in Expt. #3 to get T_b (1 σ) = 6.5 K (0."2/θ) for Δv = 0.5 km s^{-1}, ν= 294 GHz. Clearly, relaxing θ to $\gtrsim$ 1" is the only way to make detection of these lines feasible. If, however, the filling factor for the current 1' beams is considerably less than one, the lines will be brighter for the interferometer and the experiment will be easier.

Experiment #5 Absorption Lines Against Continuum Sources

The RMS noise in an 8 hour integration with 0.5 km/sec velocity resolution and 1" spatial resolution at 230 GHz is ~ 0.1 K. Given that one expects to find compact H II and dust regions with brightness temperatures greater than 50 K, the study of molecular absorption lines against these sources is possible. For example, an A_v of 5-10 may correspond to an optical depth of ~ 1 in ^{13}CO J = 1 → 0 and would result in an absorption line with a depth ~ 60% of the continuum level.

Experiment #6 Detecting Recombination Lines to Study the Velocities in Stellar Winds

Here modest spectral (6 km s^{-1}) and spatial resolution (0."6) are sufficient. Using the sensitivity equation in experiment #3, we have ΔT_b (1 σ) = 0.4 K at ν = 100 GHz (H39α or H40α) in one day. At these frequencies, one expects the line brightness to roughly equal the continuum brightness. Ultracompact H II regions and/or ionized stellar winds should be detectable in many outflowing regions since we suspect many are optically thick at centimeter wavelengths.

Experiment #7 Detection of Protostellar Clumps, Bipolar Outflows, or Disks Throughout our Galaxy

We showed in experiment #2 that protostellar cores could be detected, but not resolved at 25 kpc. For small distances, they can also be resolved. The protostellar condensation in B335 produce 0.5 Jy in the continuum at 1 mm. Since B335 is 400 pc away,

$$\Delta S_\nu = \frac{1.2 \text{ mJy } (Tsys/100)}{\{(D/10)^2 [\Delta t_{min} \Delta\nu(\text{GHz})(N_B/210)(n_a/n_m)]^{1/2}\}}$$

(Hjellming). Our usual conventions lead to

$$\Delta S_\nu = \frac{0.3 \text{ mJy } (Tsys/500)}{[\Delta t(\text{days})]^{1/2}}$$

leading to a 3σ detection in one day out to 10 kpc, and the warmer condensations should be detectable to larger distances.

Impact on Array Design - Molecular Clouds Working Group

For the scientific problems considered by this group, good performance at high frequencies is considerably more important than baselines longer than 1 km. The most important angular scales are 0."2 to 30". A few experiments require longer baselines. We need higher spectral resolution ($\Delta\nu$ as small as 10 kHz) than given in the straw man complement. We would like to be able to observe in several frequency bands (e.g. $2 \rightarrow 1$ and $5 \rightarrow 4$ CS) simultaneously and we certainly want a flexible IF and backend system so that many lines in the same band can be simultaneously observed. Double side-band receivers will allow increased flexibility and it is desirable to be able to do line and broadband continuum measurements simultaneously. Polarization studies are important for magnetic field measurements.

The emphasis on high frequencies in this group arises from two sources: the realization that dust emission will be a very powerful tool and the realization that CO $2 \rightarrow 1$ is always preferable to CO $1 \rightarrow 0$ as long as the atmosphere is good at $2 \rightarrow 1$. The latter point can be seen by comparing sensitivities at $2 \rightarrow 1$ and $1 \rightarrow 0$ for a <u>fixed</u> spatial resolution θ and velocity resolution Δv (km s^{-1}).

$$\frac{\Delta T_b\,(2 \rightarrow 1)}{\Delta T_b\,(1 \rightarrow 0)} = \frac{T_{sys}\,(2 \rightarrow 1)}{T_{sys}\,(1 \rightarrow 0)} \quad [(115/230)^{3/2} = 0.35].$$

Then for $T_{rcvr} = 100\,(\nu_{GHz}/100)$ K and

$$T_{sys} = T_{rcvr} \exp\,[\tau_1 \sec \zeta] + T_{atmo}\,[\exp\,(\tau_1 \sec \zeta) - 1]$$

Since $\tau_1 \gtrsim 0.20$ for CO $1 \rightarrow 0$ because of O_2, τ_1 for CO $2 \rightarrow 1$ need not be worse at a good site.