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LOW Z EXTRAGALACTIC WORKING GROUP REPORT

Contributors: T. Bania, Boston U.; L. Blitz, Chair, U. of Maryland; P. Crane, NRAO; J. Gallagher, NOAO; J. van Gorkum, NRAO; S. Gottesman, U. of Florida; P. Ho, Harvard U.; K. Y. Lo, Caltech; L. Rickard, Howard U.; N. Scoville, Caltech; P. Solomon, SUNY Stony Brook; A. Stark, AT&T, Bell Labs; R. Wilson, AT&T, Bell Labs; and M. Wright, U. of California at Berkeley

The proposed millimeter array as described in "The Summer 1985 Concept of the Proposed NRAO Millimeter Array" by R. M. Hjellming will acquire fundamentally new data on the structure and evolution of galaxies to distances $z \simeq 1$. Useful images of the molecular content of galaxies can be obtained at a resolution of 0"1 of arc, a resolution attainable for imaging the extended structures of galaxies only by the Space Telescope, and by no other instrument working at wavelengths outside the radio region. The molecular star-forming material in the entire Shapley-Ames catalogue can be studied with resolution comparable to the best optical images and with sensitivity sufficient to detect most giant molecular clouds within galaxies at distances less than 40 Mpc (considerably farther than the Virgo cluster). This instrument will lead to a new understanding of evolutionary processes in galaxies by allowing us to follow in detail the flow of interstellar matter through molecules into stars for a variety of galaxy types in a wide range of galaxian environments.

(1) General Considerations

The proposed MMA would collect useful data from galaxies both in the continuum and line modes. We therefore consider separately the science that can be addressed by operating in each mode. In the continuum, we recommend that the instrument be capable of observing to frequencies as high as possible, preferably to 350 GHz. Continuum observations would be primarily of dust, compact non-thermal continuum sources, very young supernovae, and HII regions.

Line observations are likely to be most frequently done at CO transitions and a capability of observing to 345 GHz (J = 3-2) is highly desirable, if the instrument is situated at a sufficiently high site ($h \gtrsim 3{,}000$ m). The consensus of the group is that the highest possible site is desirable, especially since little effective line work can be done at baselines $\gtrsim 3$ km (see below). We have considered the following classes of research which can be done with the MMA: global properties of disk galaxies, galactic centers including active nuclei, galactic disks including spiral structure, molecular clouds and the interstellar medium.

We adopt the following parameters from the J = 1-0 CO emission from particular classes of objects:

Table 1
J=1-0 CO Parameters

Type	Peak$\langle T\rangle$ (K)	ΔV (km sec^{-1})	Scale Size
Orion Core	100	10	0.5 pc
GMC (local)	2.5	5	50
GMC (inner galaxy)	5	10	50
Galactic Center (Milky Way)	5	250	150
Central Molecular Annuli (N1068)	0.5	50	1 kpc
Global Integrated (Milky Way)	0.5	50	20 kpc
Global Integrated (Virgo Cluster)	0.2	250	5 kpc

From the Hjellming memo, an 8h track, 300 m baseline, Y21 configuration and natural weighting provides ΔT_b=0.64 mK at 1 GHz frequency resolution and a spatial resolution of 1"30 for T_{sys}=100 K. ^{12}CO observations in good weather at this T_{sys} generally provide T_{TOT} = 400 K, although this might be better at a high site. Most extragalactic CO observations could combine orthogonal polarizations from dual channel receivers; the ΔT rms is lowered by $\sqrt{2}$. Therefore, since we require 2σ per pixel, the limiting sensitivity we consider is 7.7 mK/GHz at 1"30 resolution. This is equivalent to

$$\Delta T_{rms}(3\sigma) = 17mK\sqrt{\frac{260}{V}}$$

on a 300 m baseline, where V is the velocity resolution of a particular observation or

$$\Delta T_{rms}(3\sigma) = 1.7mK\sqrt{\frac{260}{V}}$$

on a 3km baseline, giving a resolution of 0"13. Of the sources listed in Table 1, the brightest sources are galactic centers; the extended emission at the center of the Milky Way is marginally detected in several pixels at a distance of 100 Mpc. Few sources are likely to be as much as 10 times brighter (requiring an average ⟨ T ⟩ of 50 K over 150 pc), thus we expect little use of the MMA at baselines much larger than 3 km for extragalactic CO observations.

For nearly all problems we considered, we expect the best imaging results using the CO J = 2-1 line. We therefore recommend that the instrument be sited such that it is useful at 230 GHz for as large a fraction of the year as possible. Furthermore, because most galaxies are extended relative to the primary beam out to large redshifts, the mosaicing capability of the proposed MMA is essential for the overwhelming majority of extragalactic observations.

(2) Line Observations

We list below the distances to which four classes of objects could be detected in CO with the proposed MMA:

Table 2
Maximum Practicable Distance of Observation

Object	Maximum Distance (Mpc)	Comment
Orion Core	3	(Local Group - 0"1 resolution)
GMC	50	(includes Virgo Cluster - 1" resolution)
Galactic Centers	300	(at 0"1 resolution)
Integrated Galaxies	3000	(at 1" resolution)

Since the parameters in Table 1 are not the largest or brightest in each class, extreme examples could be detected at even larger distances. In each case above, the objects would subtend only one pixel at the limiting distance and could be resolved at smaller distances (except for GMCs which are resolved only at distances ⟨ 10 Mpc) assuming they are like their Milky Way counterparts. These distances assume observations made in the J = 1-0 line of CO. For observations in the J = 2-1 line, assuming equal signal strength and comparable system temperature, one obtains four times the sensitivity for an object at the same distance, or, at the same sensitivity, one can observe objects twice as far as is shown in Table 2.

In the Milky Way a large fraction of the high surface-brightness CO is from GMCs. By extension, the MMA will be able to map most of the molecular emission from all the galaxies in the Shapley-Ames catalogue. It will be possible to determine in detail the relationship molecular clouds have to spiral structure, how molecular gas is distributed in detail, and what relationship the molecular gas has to star formation and the general interstellar medium in galaxies of all morphological types in a large variety of environments. Because the integrated emission from galaxies can be detected to such large distances, it will be possible to investigate how the molecular content affects the evolution of galaxies. The integrated CO emission from an entire rich cluster of galaxies could be observed, for example, with a single 8h integration if the MMA had a bandwidth of 5000 km s^{-1} and 200 km s^{-1} filter widths. Furthermore, within individual galaxies, the global gas kinematics will be observable with unprecedented resolution. The determination of H_o using tidally limited GMC diameters as objects of known physical size, may be possible with the MMA.

The structure of individual molecular clouds can be observed to a size scale of 2 pc for local group galaxies, and the counterparts of the galactic high latitude molecular clouds should also be detectable. Thus the structure of individual molecular clouds can be probed in many different galactic environments. Furthermore, with a broad bandwidth continuum channel it will be possible to map GMCs and the bright HII regions associated with them in a single observing period to get a detailed look at the star formation process in a variety of environments. (Protostellar molecular disks, and bipolar outflows similar to those observed in the Milky Way would be marginally detectable, but unrecognizable even in M31 and M33. Similarly, SiO masers from late type stars would be undetectable with the MMA even in M31 and M33.)

The MMA can detect HCO+ to a level ~2% of the CO brightness to 10 Mpc, from which the cosmic ray ionization rate and its variation in galactic disks can be determined. Also, HCN and CS can also be observed and mapped in galaxies within 10 Mpc if extrapolations can be made from current observational data. Useful information on the ^{13}CO isotope will be obtainable for many galaxies as will $C^{18}O$ in galactic centers. DCN emission should be detectable in dense GMC cores in nearby galaxies.

When combined with HI, Hα and radio continuum data, it will be possible to obtain a fairly complete picture of global properties of the interstellar medium, and the effects of spiral structure, HII regions and supernovae in a large number of galaxies. The kinematic information obtained from the MMA will be superior to all of the other dense ISM tracers, however. Hα is subject to severe extinction effects and the spatial resolution at CO will be more than an order of magnitude greater than what is possible in HI at the VLA. The high spatial resolution is of critical importance in at least two areas: determining the run of gas scale height with radius in edge on spirals and the mapping of central bars. The former is an important datum in determining the structure of possible non-luminous halos, the latter in testing models of barred galaxies. High resolution studies of non-spiral systems will allow a detailed comparison to be made of properties as a function of morphological type.

Galactic centers are a main line of research for which the MMA will be uniquely suited on scales from 5 pc at the Virgo cluster to 100 pc at a distance of 200 Mpc. Studies of the centrally concentrated molecular gas of nuclear regions will show features at 0"1 resolution, a resolution complementary to the best currently planned optical facilities. These highly obscured regions are likely to be inaccessible at optical wavelengths. It may be possible to do absorption experiments toward galactic nuclei to determine whether circumnuclear gas is falling in or flowing out. Because of the brightness of the nuclear molecular gas, it will be possible to observe nuclear regions to 300 Mpc. This volume contains a large number of galaxies with Seyfert and starburst nuclei. The MMA will doubtless yield new insight for these unusual phenomena.

(3) Continuum Observations

Although we expect that the MMA will be used as a line instrument most of the time, the science it will do as a continuum instrument is also exciting. The MMA will, for example, be uniquely capable of arcsecond resolution imaging at $\lambda = 1$ mm of the dust emission in large GMCs and the nuclei of galaxies. Since the dust radiation is optically thin and relatively insensitive to temperature at these wavelengths, the data collected will be a reliable probe of the dust masses. Because dust emission decreases as λ^{-4}, the 1 mm capability of the full array is essential for these studies. GMC regions like W51, W59, and Orion A, which contain 10^4 $M_\odot$ of dust could be detected to distances of ~5 Mpc, encompassing M33 and IC342. Furthermore, the MMA will provide the opportunity to observe dust complexes in galactic nuclei out to cosmologically interesting distances

(~200 Mpc!). Imaging of such regions at a resolution of 100 pc can be done at the distance of the Virgo cluster.

The MMA will also be an important source of data for compact continuum sources in the centers of galaxies. In particular elliptical galaxies sometimes contain compact nuclear radio sources with flat non-thermal spectra such as Vir A, Cen A, Per A. The resolution provided by the high frequency of operation of the MMA, as well as the data gathered on polarization and high frequency variability will increase the understanding of these phenomena.

Very compact HII regions will also be detectable in local group galaxies, and probably beyond. The compact stage of supergiant HII regions such as NGC 604 and 30 Dor have never been observed. These are much more luminous than the most luminous galactic HII region. Since the most luminous of the galactic compact HII regions is near the detection limit of the MMA at the distance of M33, the precursors of NGC 604 type objects should be easily detectable.

Lastly, the MMA provides an important opportunity to observe the very early stages of radio supernovae because millimeter wave observations make it possible to see through the circumstellar material at very early times. For example, the radio archetype SN I, SN 1983n, would have been transparent at 100 GHz within a few hours after the explosion, long before optical maximum. The millimeter observations may allow us to observe the initial acceleration of relativistic particles and give a new view of the properties of the expanding envelope of the star. Also, the early radio light curve will be determined by the mass loss in the last few years before the explosion, yielding unique data on the final few moments of stellar evolution.