MILLIMETER ARRAY
SCIENTIFIC MEMO NO. 1

National Radio Astronomy Observatory

MILLIMETER ARRAY REQUIRED SENSITIVITIES
EXTRAGALACTIC CO

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(9 August 1985)

1. Available Data

There isn't a lot of data on the sizes, shapes or intensities of extragalactic CO clouds. Most of what exists comes from either the Caltech interferometer, from high resolution data obtained at Nobeyama, or from placing Galactic clouds at large distances. First, let's discuss what the interferometer has observed.

(a) Existing interferometric data

As of 11/13/84, Fred Lo has maps of CO emission from IC 342, M82 and M51 produced with the interferometer. The following table summarizes these results:

Table 1. Summary of Interferometric Observations

Galaxy	Beam (7")	Peak TB	Comments
IC 342	150x150 pc	12 K	Ap. J. (Letters) 282, L59
M82	150x150 pc	15 K	Done with one filter encompassing entire linewidth. Entire single dish flux probably recovered.
M51	300x300 pc	7 K	Three fields. 3 kpc structures with strong velocity gradients along them. 7:1 arm/interarm contrast. 50% of single dish flux missing. Linewidths like Galactic GMCs.
Maffei 2			Private communication, data uninterpreted.
NGC 6946			Private communication, data uninterpreted.
NGC 253			Private communication, data uninterpreted.

These brightness temperatures seem rather high if one contrasts them with computer simulations placing Galactic GMCs at extragalactic distances.

(b) High resolution single dish data

Turner finds some indications that the definition of spiral arms becomes more striking in the J=2-1 line of CO as compared to the J=1-0 line.

(c) Galactic GMCs at large distances

Blitz (1978) estimated line strengths and sizes for local GMCs in the Milky Way. His results are summarized in Table 2, which also includes parameters for his (1981) study of GMCs in M31.

Table 2. Summary of Single Dish Observations

Galaxy	Size	Peak TB	Comments
Milky Way	46x46 pc	1.9 K	Local GMCs (Blitz 1978) 0.5" at 20Mpc!
M31	200x200 pc	0.2 K	GMC Survey (Blitz 1981) 2" at 20 Mpc!

When account is taken of beam dilution, the brightness temperatures of the GMCs in these two galaxies are practically identical. Apparently, the high brightness temperature clouds observed so far with interferometers within the central few kpc of galaxies are warmer than the GMCs observed in the Milky Way and M31 at radii of 8-10 kpc. Whether this effect should be attributed to excitation or to larger cloud sizes is not well determined.

(d) ^{13}CO

For the Milky Way GMCs, the strength of the ^{13}CO line is typically 0.2 times that of the ^{12}CO line. Similar ratios have been reported for other galaxies, but no interferometric data are yet available. Two galaxies with unusually bright 12CO lines also have unusually bright ^{13}CO lines, though lower than normal $^{12}CO/^{13}CO$ ratios. In M82, Stark (1981) reported the strength of the ^{13}CO line to be only 0.03 that of ^{12}CO. In IC 342, Young and Scoville (1982) found the strength of the ^{13}CO line to be only 0.08 that of the ^{12}CO line.

2. What do we need?

(a) Model clouds

We will parameterize four sorts of extragalactic molecular cloud and use the resulting models to determine which sorts will be observable by a millimeter array at various resolutions and frequencies. These four cloud sorts correspond roughly to (1) a warm-centered giant molecular cloud, (2) a massive warm and extended giant molecular cloud, (3) disk emission of the sort seen at the Milky Way CO emission peak, and (4) disk emission of the sort seen at the solar circle.

Because the Orion Molecular Cloud is a nearby object with which most people have some familiarity, and is a good example of a warm-centered giant molecular cloud of mid-range mass, we use it as one of our standard clouds. We have taken maps of ^{12}CO and ^{13}CO in OMC1 from published observations made with the MWO and Columbia telescopes and estimated the brightness averaged over beam sizes appropriate to the Millimeter Array in 90 m, 300 m, 1 km and 2 km configurations. The result of this process is a simple model of the cloud. Brightness temperatures for different scale sizes are given in Table 3.

One of the largest molecular clouds in the Galaxy is the Sgr A molecular cloud. This cloud is large enough and bright enough that it could be observed at a considerable distance, and it was chosen as representative of the most luminous clouds. Unpublished maps of ^{12}CO from Harvey Liszt and maps of ^{13}CO from Gary Heiligman's thesis were used to establish models for this sort of cloud. Brightness temperatures for this model cloud are also given in Table 3.

To establish a model for CO in the disks of galaxies, we adopt the disk of the Milky Way as a paradigm. We further distinguish two regions in the disk, which correspond to the "molecular ring," where CO emissivity peaks, and to the solar circle.

Two limiting cases still must be distinguished according to whether molecular complexes in the galaxies are resolved. When the projected dimension of the synthesized beam is large compared to typical molecular cloud sizes, about 20-50 pc, the emission profile is an average of the many sources in the beam.

If one viewed the peak of the annulus of the Milky Way face on with a beam of about this size, the appropriate integrated intensity of an average profile would be approximately 15 km/s, yielding an average brightness across the profile of <0.2 K. The integrated brightness follows from the intensities of approximately 20 K km/s per kpc of path seen in the galactic plane multiplied by the effective thickness of the gas disk, 1/8 kpc. The linewidth follows just from measurements of the cloud-cloud dispersion. For ^{13}CO Liszt, Xiang and Burton quote emissivities about a fifth of this at the peak of the annulus. An observation of a face-on galaxy at the solar circle would yield a smoothed brightness at least a factor of three lower for ^{12}CO, and a factor of at least four lower for ^{13}CO. Changing the assumed viewing angle results in a greater integrated intensity, but not necessarily a higher average intensity because the linewidth will usually increase as the disk is viewed more nearly edge on.

If one viewed the peak of the annulus with a finer beam, individual cloud contributions of the order of 3-4 Kelvins might be sampled. In constructing our model we have used maps of ^{12}CO and ^{13}CO emission from the Rho Oph molecular cloud as our guide.

We have then four models of clouds in two CO species which we will place at distances of 1, 5, 10 and 20 Mpc in order to define the sensitivity of the Millimeter Array to each sort of cloud. For the model of the Millimeter Array (MMA), we have adopted the design sketched in the Millimeter Array Newsletter, Vol II, No. 1. We have used a SSB receiver temperature of 1 K/GHz and included a model atmosphere with a 4 mm column of water, typical for the MWO or Kitt Peak sites in winter. We have assumed a 12 hour integration with 21 ten meter antennas over a 5 MHz frequency interval at the J=1-0 lines of both molecules.

In Figures 1-4 we plot the brightness temperature sensitivity of the MMA against the brightness temperature of the model clouds at the appropriate resolution of the array.

It is quite apparent that the solar circle disk emission will probably not be detectable in galaxies much more distant that 1 Mpc. Furthermore, by 5 Mpc even the peak of the molecular ring is, in the average, beyond all but the most compact configurations of the array. Nonetheless, the 300 m configuration still provides a resolution approximately comparable to the size of a GMC in the Milky Way. At 10 Mpc distance, even a fairly massive hot-centered cloud such as OMC-1 is at the limit of detectability. Since for this cloud an ever-narrowing beam reveals an ever-increasing brightness temperature, to the limit of resolution at this distance, the OMC-1 cloud might be detected in all configurations of the array. Approximately 85% of all extragalactic CO measurements to date have been in galaxies within 20 Mpc of the sun. At a distance of 20 Mpc, the distance of the Virgo cluster, only the very extended massive galactic center type clouds could be detected by the array. The brightness temperature of these clouds are primarily determined by beam dilution. Once these clouds are resolved, their brightness temperature may not increase on ever-diminishing scales, and so unlike our OMC-1 paradigm, the detectability of these clouds may not be a strong function of resolution. We can test these models against the results mentioned above for the OVRO interferometer. If a description of that instrument is plugged into the model for the MMA sensitivity, for example, the predicted sensitivity is within 25% of the numbers quoted by observers. If the model instrument is confronted with the model clouds, we can predict which sorts of clouds will be observable with that instrument. We find that only extended high brightness temperature clouds, similar to our model of the galactic center clouds, will be observable. This prediction is in accord with the observations.

In a second set of figures (5-7) we show the results of the confrontation of our MMA model with the models of ^{13}CO emission from molecular clouds. It appears that the array might be capable of detecting ^{13}CO in OMC-1 and galactic center-type clouds to a distance of several Mpc. As close as 1 Mpc, even the peak of the Milky Way ^{13}CO distribution might be observable. Testing the model against the Caltech observations, we estimate that the sensitivity attainable would be sufficient to detect galactic center type ^{13}CO clouds at a distance of 1 Mpc. Unfortunately no such clouds are known within 1 Mpc and the interferometers have not yet detected extragalactic ^{13}CO, consistent with the predictions of our models.

The discussion has centered so far on the J=1-0 lines of CO. The main isotopic line is probably optically thick, so we have used the same models for the J=2-1 and J=3-2 lines. What one loses to the O_2 line at 115 GHz is roughly comparable to what one loses to H_2O at 230 GHz. Therefore the main difference in the performance of the MMA at the two lines will probably depend upon receiver temperature, resolution and atmosphere more than upon any changes in the brightness temperature profile of the extragalactic clouds (Figures 8 and 9). This may not be true for a comparison of the less optically thick J=1-0 ^{13}CO emission from the clouds to the thicker J=2-1 emission. Although the atmosphere is a worse problem at 220 GHz than at 110 GHz, the extragalactic clouds may be brighter by up to a factor of about four. However, the increasing optical depth of the emission may make it a less sensitive probe of mass. At the J=3-2 CO line, there is no data on extragalactic clouds. It seems likely that the brightest galaxies, such as M82, will be detectable on very good days. Although the body of evidence on the behavior of the J=3-2 CO line in our galaxy is not yet conclusive, it appears to me that the typical conditions in the great majority of clouds which emit in the J=1-0 line are not sufficient to excite appreciable emission in the J=3-2 line. I believe the data available supports this view, and that only the cores of OMC1 of Sgr A-like clouds will be detectable by the MMA during exceedingly good weather. It will not be possible to detect the J=3-2 ^{13}CO line.

It appears to be beyond the grasp of the MMA to detect disk CO at the distance of the Virgo cluster. It may not, however, be very far beyond the grasp of the instrument as we have modeled it here. Young, Scoville and Brady (Ap. J. 288, 487, 1985) recently detected CO in eighteen of twenty-five Virgo cluster spiral galaxies. Their measured peak temperatures have been placed at the appropriate position in the figures (50" 5 kpc). It appears that by degrading the velocity resolution somewhat the MMA should be able to map the emission in most of these galaxies, assuming recovery of the single dish flux. The effect of the cluster environment on galaxies is a topic of a great deal of current research, and it would be very desirable for the MMA to be able to address this topic directly. For example, there is evidence that star formation proceeds at a more relaxed pace in spirals near the core of the cluster. If the character and extent of star formation is really quite different in these galaxies, attempts to measure the Hubble Constant through Space Telescope measurements of Cepheid light curves might be called into question. We suggest that attainment of sensitivity necessary to observe Virgo spirals be a design goal for the MMA.

The other lines which trace high density, such as CS, HCO+ or HCN, might also be detected with the array. The typical core sizes of garden variety clouds in these lines are somewhat less than 1 pc. They will be diluted by the canonical 0.5" beam at 1 Mpc, and the 3 mm line of HCO+ in OMC1 would, for instance, lie within one spatial and velocity resolution element with a brightness temperature of only 0.7 K in a 3 MHz filter. The Sgr A cloud has somewhat stronger emission over a wider spatial and velocity range, and would have a brightness temperature of 2-3 K in spread over several spatial and velocity resolution elements. In the J=3-2 line of HCO+ the line intensity would be only 1-2 K, but it would still spread over several resolution elements. Extragalactic CS has not been detected, but with better receivers at the J=1-0 line at 49 GHz, and with the somewhat broader main beam of the antennas, it should prove a good tool for probing denser material.

In summary, the sensitivity of the array given in MMA Memo 21 (with correction factor) would probably be adequate for mapping of GMCs with a sensitivity adequate for pinpointing regions of massive star formation to within a few km/s in velocity and a few pc in projected distance. ^{13}CO and other molecules might be detectable at 1 Mpc at the limits of sensitivity in the smaller GMCs such as OMC1, but a larger cloud such as Sgr A could still be detected to somewhat greater distances.

Table 3

Brightness Temperatures of Model Clouds

Cloud Scale	Ring	OMC1	Sgr A
1.3 pc	2.0 K	50 K	28 K
2.6 pc	1.0	30	28
8.5 pc	0.3	15	25
28 pc	0.04	3	12.5
42 pc	diluted	1	7
142 pc	diluted	diluted	2

"Disk" CO emission has been modeled as 20% of the "Ring" CO emission. Harvey Liszt contributed most of the discussion on Ring and Disk CO emission.

Figures

Figure 1. Strawman MMA sensitivity to CO J=1-0 emission from various cloud types in Table 3 at 1 Megaparsec distance. The abcissa is the log of the synthesized beam size in parsecs at that distance. The ordinate is the brightness temperature expected for the clouds in the appropriate synthesized beamsize. The line shows the sensitivity of the strawman array at four configurations, 2 km (left), 1 km (left center), 300 m (right center) and 90 m (right). Plus signs trace the expected brightness temperature of clouds mimicking the Milky Way disk at the solar circle. Diamonds trace the expected brightness temperature of clouds mimicking the Milky Way molecular ring at around 6 kpc. Triangles trace the model brightness temperatures for the Sgr A type cloud, and crosses trace the model brightness temperature for GMCs resembling OMC1.

Figure 2. Same as Figure 1 but for 5 Megaparsecs.

Figure 3. Same as Figure 1 but for 10 Megaparsecs.

Figure 4. Same as Figure 1 but for 20 Megaparsecs.

Figure 5. Same as Figure 1 but for ^{13}CO, J=1-0 emission. The new solid line which has appeared in this Figure represents sensitivity for the OVRO interferometer (inverted triangles).

Figure 6. Same as Figure 5 but for 5 Megaparsecs.

Figure 7. Same as Figure 5 but for 10 Megaparsecs.

Figure 8. Same as Figure 1 but for 230 GHz. The far right configuration represents the sensitivity of the multiple-telescope array above, similar to a 25 m configuration. Diamonds and plus signs have been interchanged on Figures 8 and 9.

Figure 9. Same as Figure 1, but for 345 GHz and 3 mm of H_2O.

Fig. 1

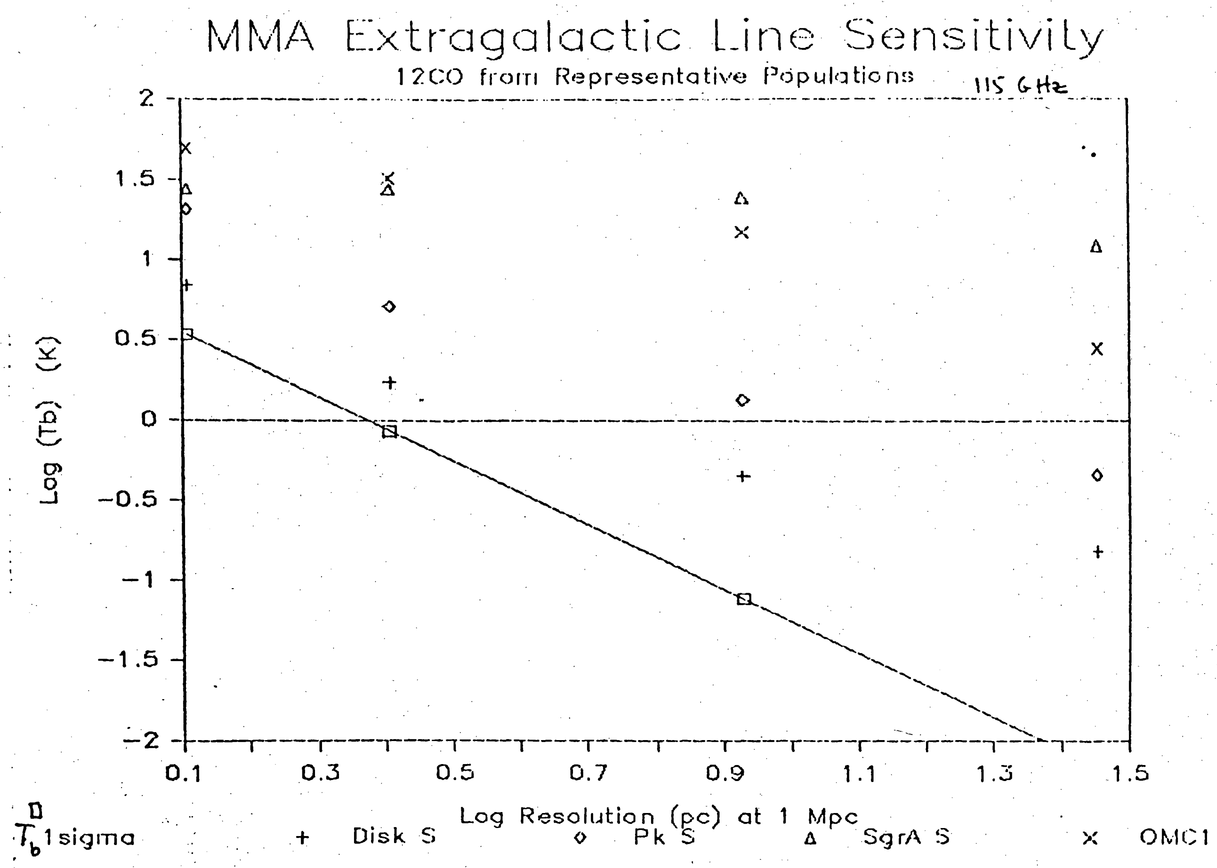
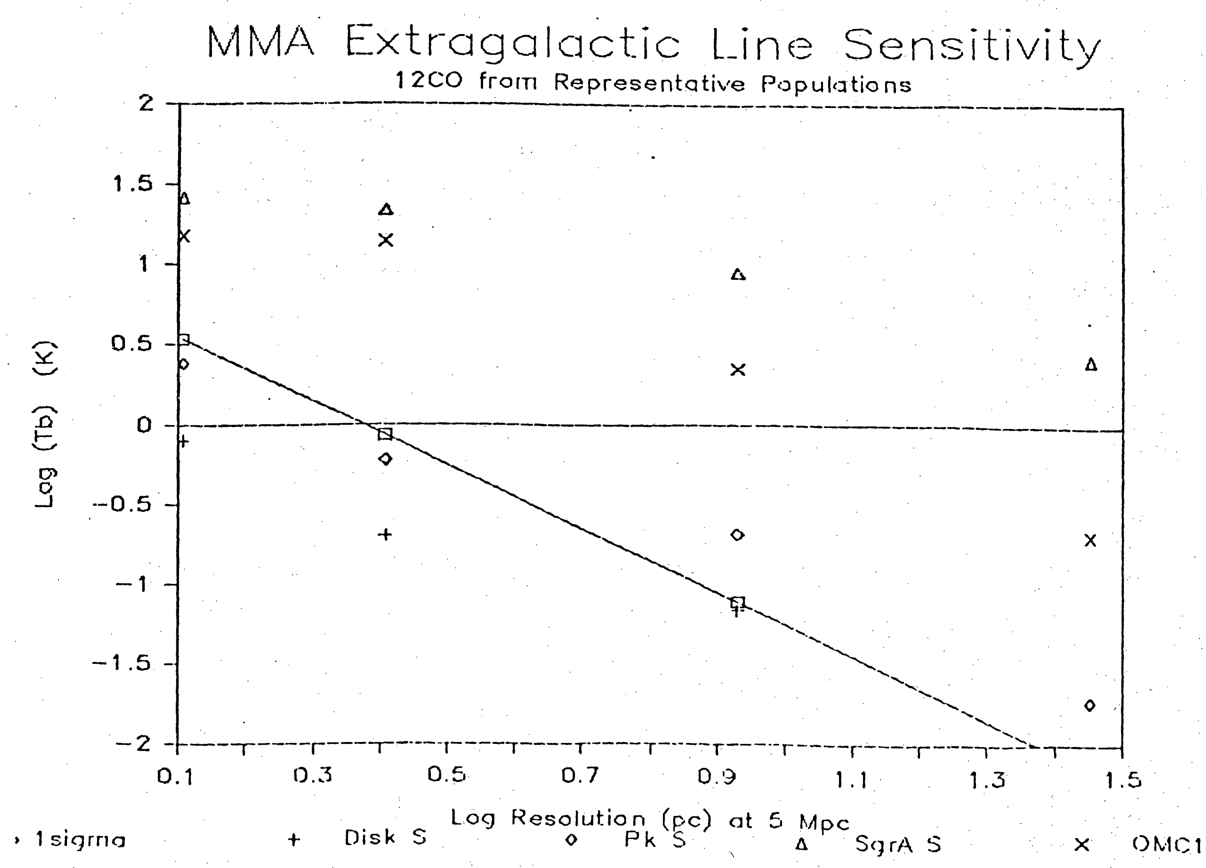

MMA Extragalactic Line Sensitivity
12CO from Representative Populations
115 GHz
Log (Tb) (K)
Log Resolution (pc) at 1 Mpc
T_b 1sigma
Disk S
Pk S
SgrA S
OMC1

Fig. 2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Log Resolution (pc) at 5 Mpc
1sigma
Disk S
Pk S
SgrA S
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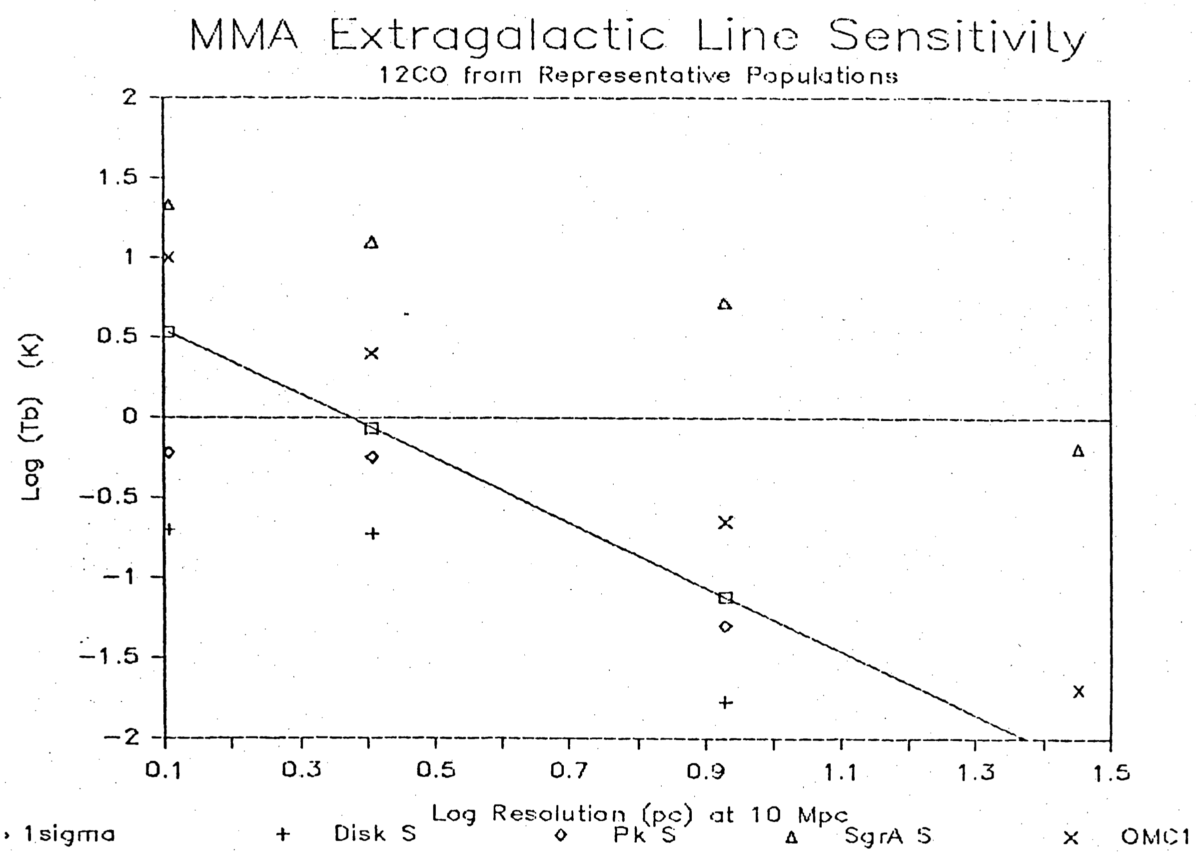
Figure 9. Same as Figure 1 but for 345 Ghz and 3mm of H_2O.

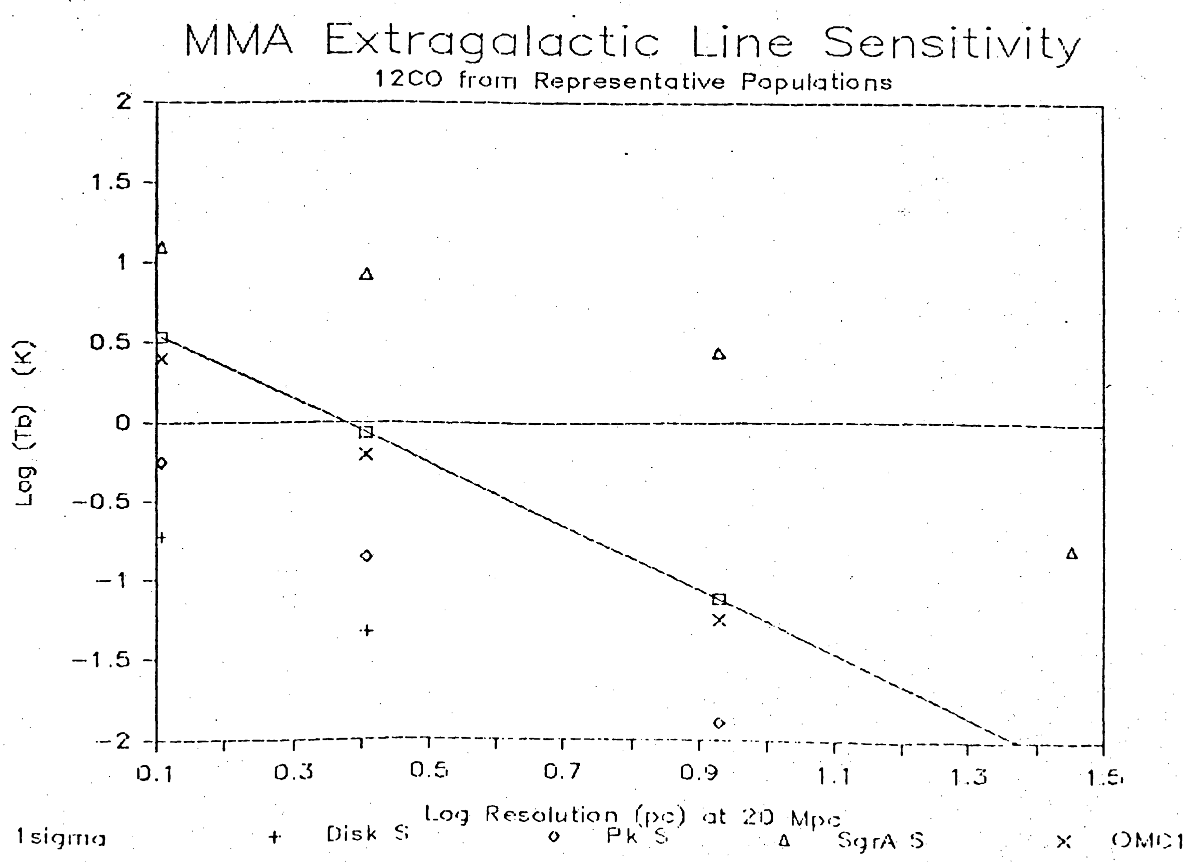
On Figures 8 and 9, the far right configuration represents the sensitivity of the multiple-telescope array alone, similar ~~equivalent~~ to a 25m configuration.
Diamonds and plus signs have been interchanged on Figs 8 and 9.

Fig. 3



MMA Extragalactic Line Sensitivity
12CO from Representative Populations
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
Log (Tb) (K)
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
Log Resolution (pc) at 10 Mpc
1sigma
Disk S
Pk S
SgrA S
OMC1

Fig. 4



MMA Extragalactic Line Sensitivity
12CO from Representative Populations
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
Log (Tb) (K)
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
Log Resolution (pc) at 20 Mpc
1sigma
Disk S
Pk S
SgrA S
OMC1

Fig. 5

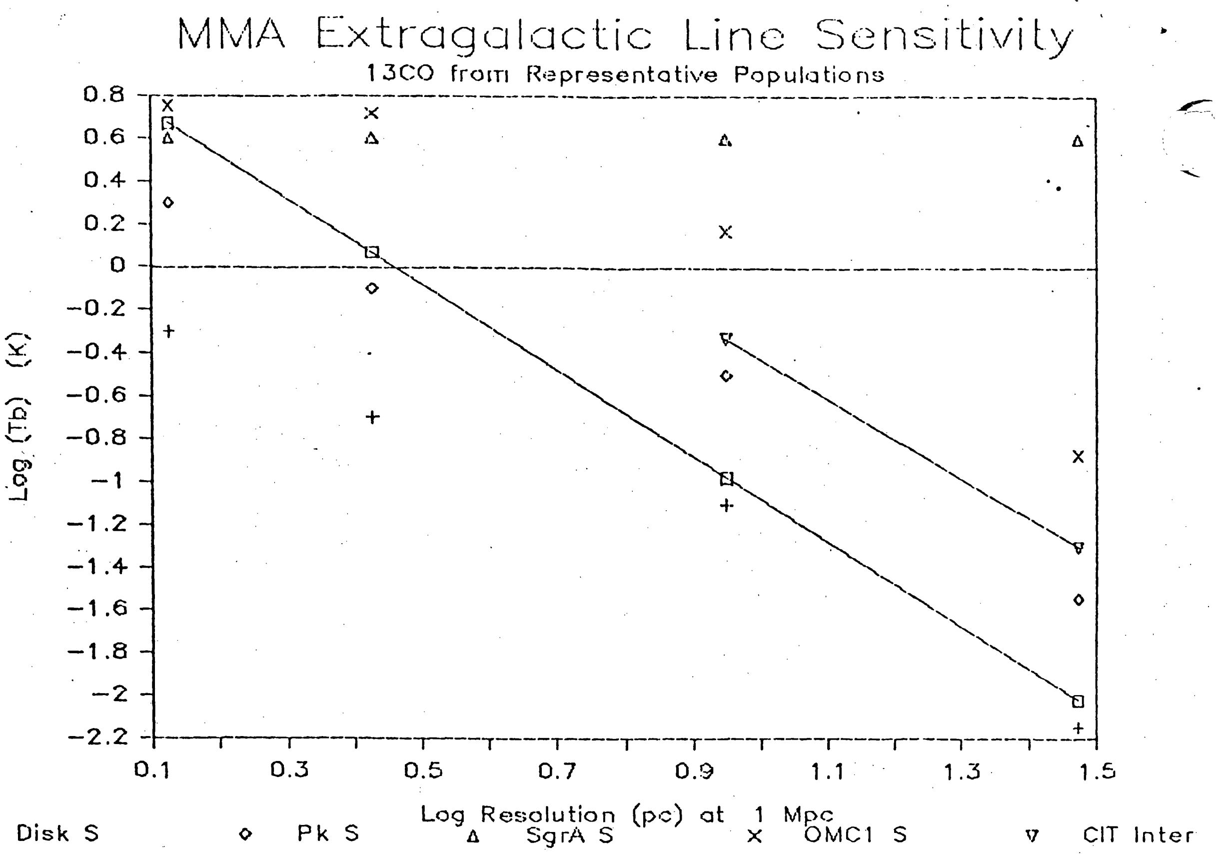

MMA Extragalactic Line Sensitivity
13CO from Representative Populations
Log (Tb) (K)
Log Resolution (pc) at 1 Mpc
Disk S
Pk S
SgrA S
OMC1 S
CIT Inter

Fig. 6

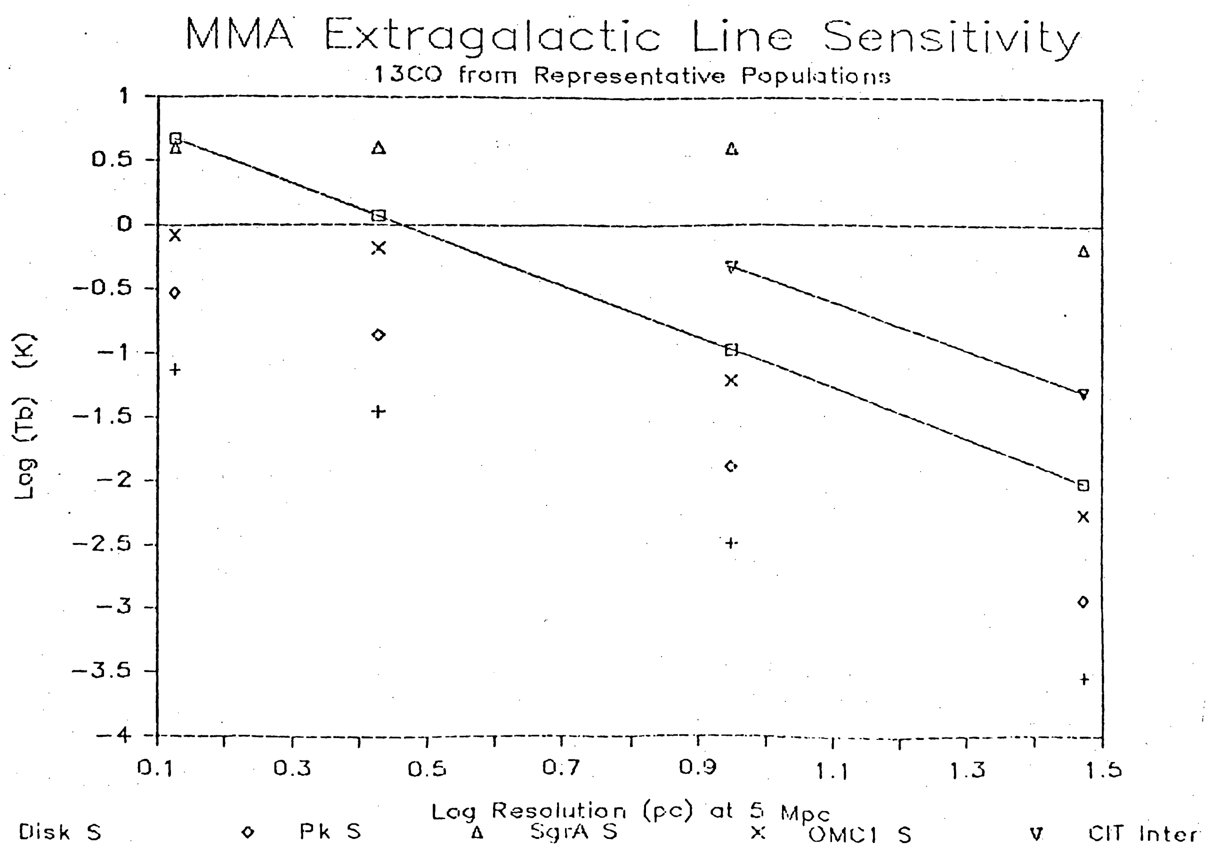

MMA Extragalactic Line Sensitivity
13CO from Representative Populations
Log (Tb) (K)
Log Resolution (pc) at 5 Mpc
Disk S
Pk S
SgrA S
OMC1 S
CIT Inter

Fig. 7

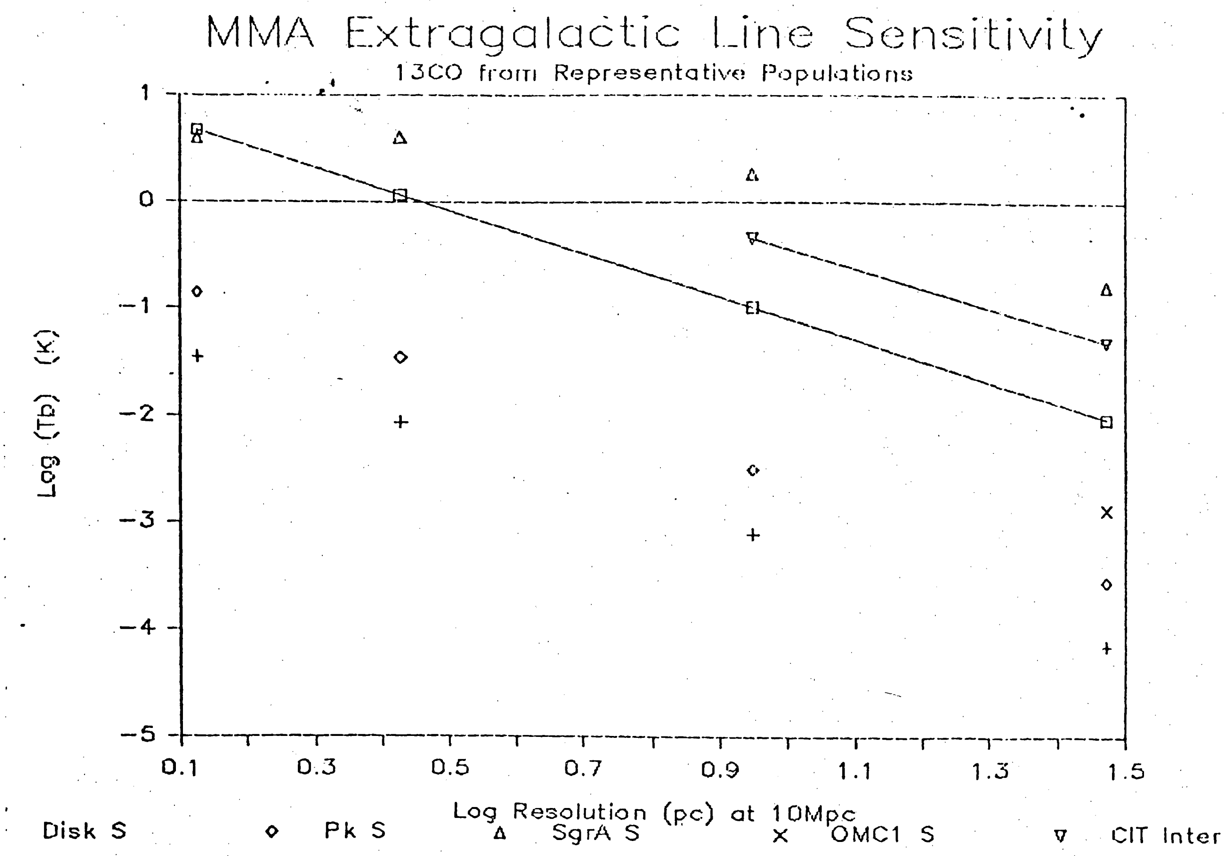

MMA Extragalactic Line Sensitivity
13CO from Representative Populations
Log (Tb) (K)
Log Resolution (pc) at 10Mpc
Disk S
Pk S
SgrA S
OMC1 S
CIT Inter

Fig. 8

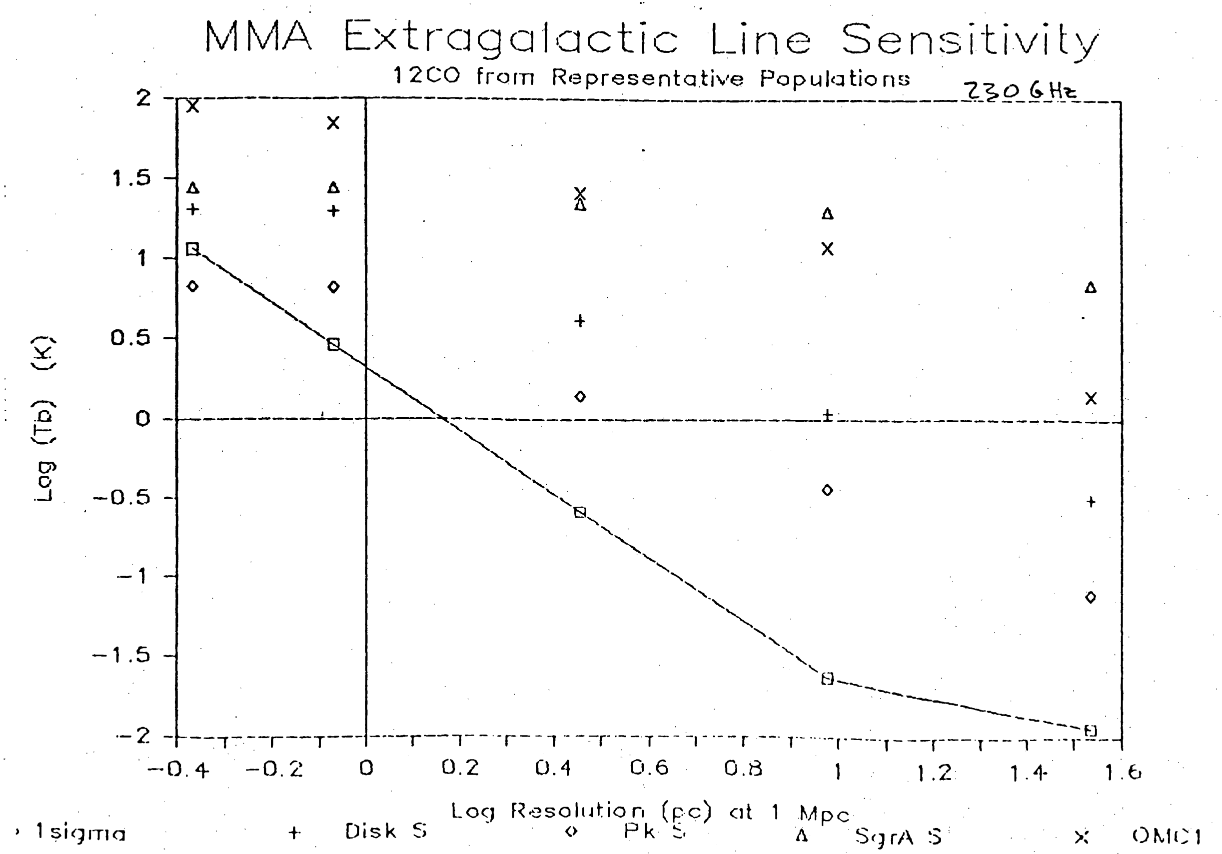
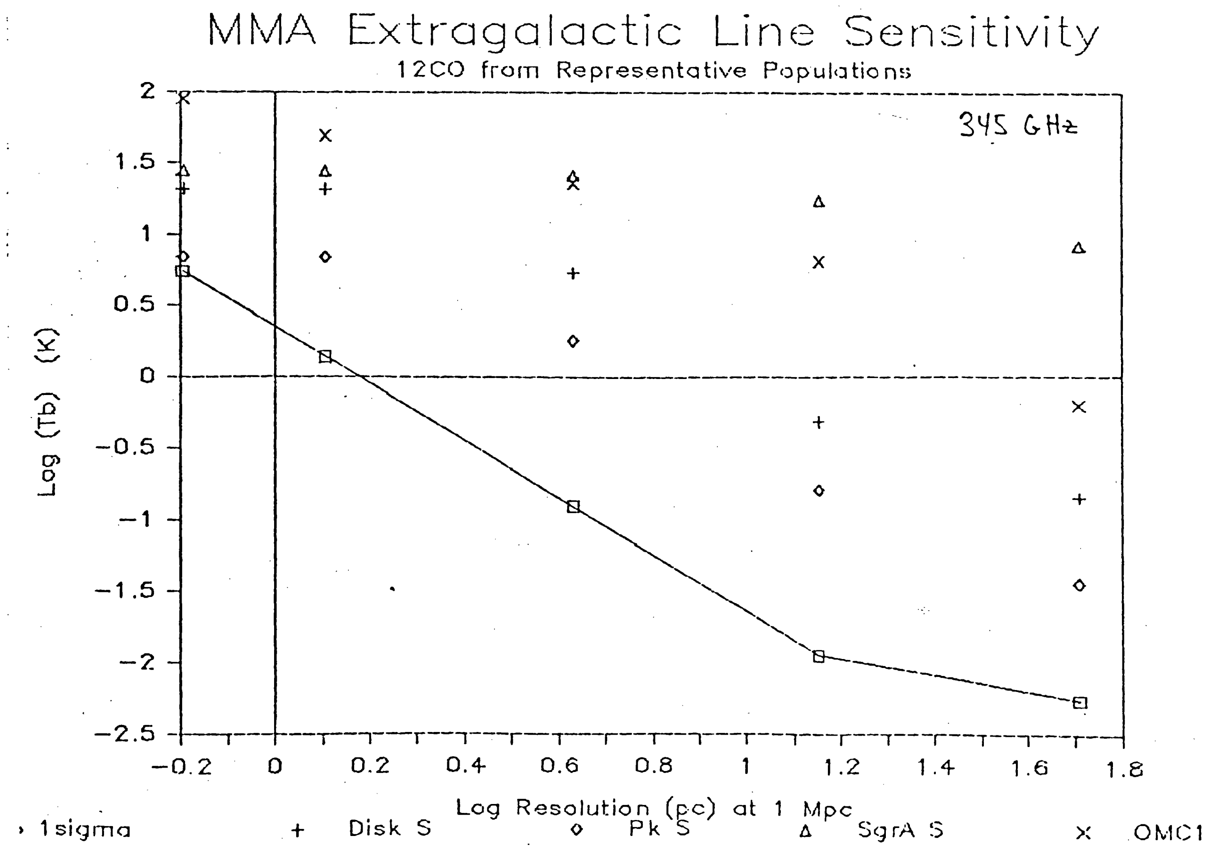

MMA Extragalactic Line Sensitivity
12CO from Representative Populations
230 GHz
Log (Tb) (K)
Log Resolution (pc) at 1 Mpc
1sigma
Disk S
Pk S
SgrA S
OMC1

Fig. 9



MMA Extragalactic Line Sensitivity
12CO from Representative Populations
345 GHz
Log (Tb) (K)
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Log Resolution (pc) at 1 Mpc
1sigma
Disk S
Pk S
SgrA S
OMC1