25 METER - MILLIMETER WAVE TELESCOPE

REPORT # 1

A 25 METER TELESCOPE FOR THE MM WAVELENGTH RANGE

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The discovery of a large number of molecular lines in the mm region of the spectrum in the past few years (Table 1) has made it imperative that NRAO develop more sensitive telescopes in the mm region. For molecular line studies this means not only larger telescopes but telescopes that can operate at the shortest possible wavelengths down to 1 mm, because the line signals become stronger at higher frequencies.

The steady increase in receiver performance leaves no doubt that receivers will achieve noise temperatures as low as 100 K and operating wavelengths at least as short as 1 mm. In 1974 Weinreb and Kerr will have a cooled mixer receiver operating from 80 to 120 GHz with a system temperature of 400 K. Jefferts and Wrixon of BTL have coherent receivers which operate at 230 GHz. The sensitivity to an unresolved source with a 25 m telescope and a 400 K receiver is a factor of 65 over the telescope and receiver used to detect the first HCN line.

Considering the receiver factor alone, the development of mm wave line receivers by BTL and NRAO has resulted in an avalanche of astronomical results. Twelve new molecules have been discovered with these receivers and the NRAO 36-ft telescope. Another ∿30 lines of known molecules have been observed with the 36-ft telescope. The study of these lines is vitally important in tracing the evolution of molecular clouds. This involves determining the chemistry taking place in these clouds. For this work relative abundances and the presence or absence of key molecules is important. The detection of new, larger molecules will give us some clue as to how far the chemistry has proceeded. The physical conditions in molecular clouds can be established by studying several transitions of the same molecule. Finally these clouds are presumed to be prime sites for star formation. The high excitation transitions of such molecules as HCN, CS, H_2O and H_2CO imply physical conditions which strongly suggest this conclusion. Most of these astronomical problems require a telescope with higher sensitivity and resolution than the present 36 ft provides. In addition the need to be able to observe several transitions of a molecule down to a wavelength of 1 mm requires a telescope whose efficiency, pointing and beam shape are still reasonable at this wavelength.

In Table II we list some important new lines which should be detectable in the 200 to 300 GHz range. Some of these lines are additional transitions of known molecules, which are particularly important in elucidating the excitation of these molecules. Other lines in Table II involve new molecules containing new atomic elements. The new elements: P, Fe, Mg and Cl lie one step down in cosmic abundance from the elements in presently known molecules. In order to compensate for their lower abundance, the detection of these new elements requires wavelengths < 3 mm where line strengths are large.

We will not comment on the uses of the proposed telescope for continuum studies of extragalactic objects. However, continuum observations at wavelengths from 3 mm to 0.3 mm are useful for interpreting molecular line observations. For example, in the Orion nebulae at cm wavelengths the emission is from the H II region which is believed to be in front of the molecular cloud. At short mm wavelengths the continuum emission appears to be coming from the dust, or from a small residual ionization, in the molecular cloud since the continuum maps resemble the molecular line maps. Hence for continuum work as well as line work it would be desirable to use the telescope at wavelengths shorter than 1 mm when the atmosphere permits.

The Atmosphere at mm Wavelengths

The atmospheric transmission at mm wavelengths is dominated by absorption lines of H_2O and O_2. The region of the spectrum from 10 mm to 1 mm is primarily affected by H_2O at 183.3 GHz (1.64 mm) and 323.2 GHz (0.93 mm) and by O_2 at 60 GHz (5.0 mm) and 120 GHz (2.5 mm). For this reason a high altitude site is desirable. Kuiper 1970 gives comparative water vapor computations for a number of mountain sites (Table III) and Findlay and von Hoerner (1972) plot the water vapor over the VLA sites in Arizona (near Kitt Peak) and the Plains of Saint Augustine for a year (Fig. 1). From this we can conclude the following average precipitable H_2O in the atmosphere.

	Elevation	Precipitable Water Vapor Winter	 Summer
White Mountain	14,200 ft	1 mm	2 mm
Kitt Peak	6,800 ft	4 mm	11 mm
Plains of St. Augustine	7,000 ft	3 mm	11 mm

For 5% of the time during the winter the water vapor drops to 1.7 mm at Kitt Peak and 0.44 mm at White Mountain. The atmospheric absorption in the mm wave range (Fig. 2) is taken from Findlay and von Hoerner (1972). In addition, the following zenith absorption measurements have been made at the 36 ft telescope (Conklin and Ulich 1973).

Frequency	Wavelength	Attenuation
70 GHz	4.3 mm	1.0 dB
85 GHz	3.5 mm	0.15 dB
115 GHz	2.6 mm	1.5 dB
150 GHz	2.0 mm	0.35 dB
230 GHz	1.3 mm	1.0 dB

The absorption at 250 GHz should not be much more than at 150 GHz since the windows have approximately the same attenuation. However, measurements at Kitt Peak do not completely support this conclusion (Conklin and Ulich 1973). Theoretical calculations of Hall (1967) give the following attenuation for the sub-mm windows with 1 mm precipitable water vapor.

Frequency	Wavelength	Attentuation
340 GHz	0.88 mm	1.5 dB
405 GHz	0.74 mm	2.5 dB

Frequency	Wavelength	Attentuation
470 GHz	0.64 mm	5.0 dB
670 GHz	0.45 mm	5.0 dB
830 GHz	0.36 mm	6.0 dB

The attenuation in dB should be multiplied by the mm of precipitable water vapor to determine the total attenuation at a given site.

The Telescope and Site

In comparing the two VLA sites (VLA Proposal, Vol. IV), the valley near Kitt Peak and the Plains of St. Augustine, the amount of sunshine for Kitt Peak is 86% and 70% for the Plains. The mean hourly wind is 7.8 and 9.6 mph and 50 yr. maximum wind is 67 and 77 mph for Kitt Peak and the Plains, respectively. Since this is for the valley adjacent to Kitt Peak, the amount of wind at the peak is probably higher and the amount of sunshine lower.

There is a strong possibility that a 25 m telescope would be incorporated into an array at a later time. Therefore, the site should be capable of accommodating a number of movable elements used in connection with the fixed 25 m.

Several millimeter telescopes are listed in Table IV. These are mostly from Cogdell et al.(1970) and the surface accuracy and efficiency quoted are not always consistent. The Aerospace and McDonald instruments have the best surface giving 1/16 to 1/20 of a wavelength at 1 mm. Philco-Ford can now make panels with a surface accuracy of 0.002". The

36-ft (11 m) telescope has a surface accuracy of 0.0055" (Conklin and Ulich 1973). The proposed 65 m telescope (Findlay and von Hoerner 1972) would have a total accuracy of 0.008". The 25 m telescope should have a total accuracy between 0.002" and 0.003". The beamwidth at 1 mm would be 10 seconds of arc so that the pointing accuracy should be 2 seconds of arc.

Additional Facilities Needed at λmm Wavelengths

In the above, we have discussed the need for a 25 m telescope usable at 1 mm. We consider this to be the most useful instrument at any wavelength, in terms of expected new scientific results, that NRAO can build in the price range $1M to $10M.

For spectral line work, it is also very important to have an interferometer capability in the λmm region. Molecules are potentially powerful probes of the physical conditions in dark cool interstellar clouds, regions which cannot be examined by any other means available to radio astronomy. At present, the amount of reliable physical information obtained by molecules is seriously limited by inadequate spatial resolution. Molecules must be observed at several transitions in order to understand their excitation, and hence their abundances and distributions within dark clouds. These various transitions typically lie in the λ7 mm, λ3.5 mm, λ2 mm ... regions. Current telescopes give only ∿ 3' resolution at λ7 mm. This resolution is completely inadequate given that observations of the same molecules at λ2 mm (current available resolution ∿50") indicate structure at least as small as 30". We expect structure at least as small as 10" to be important in interpretation.

As a single dish, the 25 m telescope has a resolution of 10" at λ1 mm, or 1' at λ7 mm. An interferometer should be capable of operating with and without the 25 m telescope. Since most molecular clouds are several arc min in size, the 25 m telescope has too small a field of view for overall synthesis. When the interferometer minus the 25 m telescope indicates the presence of small condensations and locates their positions, the 25 m telescope could then be included to examine these areas with greater sensitivity and possible higher resolution.

The larger clouds of probable interest to synthesize have sizes ∿10' at λ7 mm. Therefore, the interferometer elements would need to be no larger than ∿15 ft. However, problems of sensitivity might arise with such small elements, so perhaps 30-ft elements should be considered. A 4-element array, with the 25 m telescope acting as a fifth element on occasion, would be a suitable initial instrument. Baselines up to ∿600 ft are needed to give a resolution of 10" at λ7 mm.

It seems necessary to us that NRAO build a λmm interferometer. Some university groups in the US and in other countries are becoming involved in λmm interferometer development. However, such instruments must be flexible in operating frequency if they are to solve the problems for which they are built. Specifically, they must at least be able to operate over a range of frequencies (perhaps 20% of the center frequencies) centered at λ7 mm, λ3.5 mm, and λ2 mm. This seems beyond the scope of university-based operations in the US. Even if, as seems very unlikely, several universities build arrays, each operating at only one of the desired frequency ranges, the reliability with which one could compare maps taken with the various instruments (different calibrations, different baselines, etc.) would be much smaller than if all maps were made with one instrument. Also, unless university based instruments were open to all users, a heavy restriction would be placed on the range of problems tackled, and the science would inevitably be done in a piecemeal fashion, if properly at all.

REFERENCES

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Hall, J. T., Applied Optics, 6, 1391, 1967.

Table I

Molecular Lines Detected at mm-wavelengths

MOLECULE	QUANTUM NUMBERS	WAVELENGTH	FREQUENCY
$H^{13}CN$	2-1	1.74 mm	172.7 GHz
$HC^{15}N$	2-1	1.74	172.1
CH_3OH	10_1-10_0	1.77	169.3
H_2S	1_{10}-1_{01}	1.78	168.8
H_2CO	2_{11}-1_{10}	1.99	150.5
CS	3-2	2.04	147.0
H_2CO	2_{02}-1_{01}	2.06	145.6
DCN	2-1	2.07	144.8
H_2CO	2_{12}-1_{11}	2.13	140.8
SiO	3-2	2.30	130.2
CO	1-0	2.60	115.3
CN	1-0	2.64	113.5
CH_3CN	6-5	2.72	110.4
^{13}CO	1-0	2.72	110.2
$C^{18}O$	1-0	2.73	109.8
OCS	9-8	2.73	109.5
HC_3N	11-10	2.99	100.1
CS	2-1	3.06	98.0
$C^{33}S$	2-1	3.08	97.2
$C^{34}S$	2-1	3.11	96.4
^{13}CS	2-1	3.24	92.5
HC_3N	10-9	3.29	91.0
HNC	1-0	3.31	90.7
X-ogen	?	3.36	89.2

Table I (cont.)

MOLECULE	QUANTUM NUMBERS	WAVELENGTH	FREQUENCY
HCN	1-0	3.38 mm	88.6 GHz
HNCO	4_{13}-3_{12}	3.40	88.2
HNCO	4_{04}-3_{03}	3.41	87.9
$H^{13}CN$	1-0	3.47	86.3
$HC^{15}N$	1-0	3.49	86.0
CH_3CCH	5-4	3.51	85.5
CH_3OH	5_1-4_0	3.55	84.5
HC_3N	9-8	3.66	81.9
H_2CO	1_{01}-0_{00}	4.12	72.8
HC_3N	8-7	4.12	72.8
DCN	1-0	4.14	72.4
CS	1-0	6.12	49.0
$C^{33}S$	1-0	6.17	48.6
CH_3OH	1_0-0_0	6.19	48.4
H_2CO	4_{13}-4_{14}	6.21	48.3
$C^{34}S$	1-0	6.22	48.2
^{13}CS	1-0	6.49	46.2
HC_3N	5-4	6.59	45.5
HNCO	2_{02}-1_{01}	6.81	44.0
CH_3OH	4_1-3_0	8.19	36.6
HC_3N	4-3	8.24	36.4

Table II

Potential Molecular Lines from 200 to 300 GHz

MOLECULE	QUANTUM NUMBERS	WAVELENGTH	FREQUENCY
H_2S	3-3	1.00 mm	300.5 GHz
DCN	4-3	1.05	286.6
HNC	3-2	1.10	272.0
X-ogen	3-2 (?)	1.12	267.6
PH_3	1_0-0_0	1.12	266.9
HCN	3-2	1.13	265.9
HNCO	12-11	1.14	263.8
CS	5-4	1.22	244.9
HNCO	11-10	1.24	241.8
HDO	2_{11}-2_{12}	1.24	241.6
HCP	6-5	1.25	239.6
PN	5-4	1.28	235.0
CO	2-1	1.30	230.5
H_2S	5-4	1.31	228.5
CN	2-1	1.32	227.0
HNCO	10-9	1.36	219.8
H_2CO	3_{03}-2_{02}	1.37	218.2
DCN	3-2	1.38	217.2
H_2S	2_{20}-2_{11}	1.38	216.7
FeO	7-6	1.40	214.3
CH_3Cl	8-7	1.41	212.6
H_2CO	3_{13}-2_{12}	1.42	211.2
MgO	6-5	1.46	205.7
CH_3CN	11-10	1.48	202.4

TABLE III

PRECIP. H_2O IN VERTICAL COLUMN (mm) (Kuiper 1970)

SITE	LAT. (N)	LONG	ELEVATION		p	AC-CESS*	PRE-CIP.	SNOW†	JANUARY		APRIL		JULY		OCTOBER		25% ±
			FT.	M	(mb)				5%	50%	5%	50%	5%	50%	5%	50%	(9 Mo.)
Palomar Obs. (Calif.)	33°21′	116°52′	5600	1706	825	A	24	36	1.8	3.4	1.9	4.4	3.5	9.5	2.6	6.1	2.1
National Radio Obs.	38°26′	79°50	2700	823	920	A	44	80	1.2	4.3	2.6	8.0	12.	20.	3.4	10.	2.4
Kitt Peak Nat'l Obs.	31°58′	111°36′	6750	2064	789	A	12	4	1.7	4.4	1.8	3.7	5.5	10.9	2.3	7.1	1.9
Catalina Obs. (Ariz.)	32°25′	110°44′	8450	2580	740	A	12	5	1.1	2.9	1.4	3.0	5.1	9.7	1.9	5.5	1.5
Mt. Lemmon (Ariz.)	32°26′	110°47′	9190	2800	720	A	12	5	1.0	2.7	1.3	2.8	5.0	9.1	1.8	5.0	1.4
Humphreys Pk. (Ariz.)	35°21′	111°41′	12633	3852	629	O	24	60	0.57	1.4	0.7	1.6	1.7	4.8	0.94	2.1	0.74
Mt. Agassiz (Ariz.)	35°20′	111°41′	12356	3770	636	A *	24	60	.62	1.5	.8	1.7	2.0	5.2	1.0	2.3	0.81
Charleston Pk., Nev.	36°16′	115°42′	11920	3635	647	O *	12	10	.56	1.5	.57	1.85	1.85	3.1	1.1	2.6	0.74
White Mt., Calif.	37°38′	118°15′	14242	4340	590	O *	12	30	.44	1.1	.49	1.2	1.1	1.9	0.7	1.3	0.54
Barcroft Lab. (White Mt.)	37°35′	118°15′	12500	3510	632	A	12	30	.59	1.4	.66	1.6	1.4	2.4	.8	1.6	0.68
Wheeler Pk., Nev.	38°59′	114°19′	13058	3980	618	T *	12	60+	.47	1.2	.65	1.5	1.35	3.1	.8	1.9	0.64
Delano Peak, Utah	38°22′	112°22′	12173	3712	640	T *	16	60+	.57	1.4	.83	1.7	1.6	4.3	.95	2.4	0.78
Mt. Peale, Utah	38°.4	109°.2	12721	3880	626	O *	24	60+	.48	1.3	.90	1.6	1.6	4.5	.93	2.3	0,77
Mt. Nebo, Utah	39°49′	111°45′	11871	3620	648	T *	16	50	.57	1.5	1.0	1.9	1.7	4.4	1.0	2.5	0.86
Mt. Timpanogos, Utah	40°23′	111°39′	11750	3580	652	T *	32	100	.54	1.5	1.0	2.0	1.7	4.5	.96	2.6	0.83
Kings Pk., Utah	40°47′	110°22′	13528	4130	606	O	40	150:	.40	1.1	0.67	1.4	1.3	3.6	0.75	1.8	0.61
Pikes Pk., Colo.	38°50′	105°2′	14110	4300	593	(A)*	24	100	.40	1.0	.7	1.3	1.6	4.2	.81	1.9	0.64
Mt. Shasta, Calif.	41°25′	122°12′	14162	4317	592	O *	80	100+	.35	1.0	.47	1.2	0.93	1.7	.64	1.35	0.49
Mt. Rainier, Wash.1)	46°51′	121°46′	14150	4313	592	O *	96	400+	.38	0.95	.39	1.2	.88	1.6	.54	1.4	0.44
Mt. Fairweather, Alsk.	58°54′	137°31′	15320	4670	566	O *	32	200:	.16	0.6	.23	0.6	.7	1.6	.25	0.8	0.21
Mt. McKinley, Alaska	63°05′	150°59′	20320	6200	459	O *	16	100	0.07	0.15	0.09	0.20	0.24	0.6	0.09	0.24	0.08
Mauna Kea, Hawaii	19°.8	155°.5	13800	4215	600	A	16	+	1.2	1.5	1.0	1.8	1.3	2.0	1.2	2.3	1.1
Baja California, Mex.	31°.0	115°.6	9280	2830	717	(A)	—	—	1.2	2.6	1.35	2.8	3.5	8.2	1.9	4.7	1.5
Popocatepetl, Mex.	19°.0	98°.6	17887	5450	509	O	—	—	0.61	1.0	0.79	1.4	1.9	2.8	0.81	2.7	0.74
Road terminus 2)	19°.0	98°.6	15500	4730	560	A	—	—	.9	1.7	1.1	2.1	2.9	4.1	1.25	4.1	1.1
Mt. Bolivar, Venez.	8°.6	71°.1W	16427	5000	540	A	—	—	.6	1.6	1.1	1.7	1.5	2.8	1.6	3.5	1.1
Jungfraujoch, Swit.	46°.5	8°E	11500	3500	658	A	—	—	.52	1.5	0.6	2.0	1.4	4.1	1.1	2.7	0.74
Mt. Blanc, France	45°52′	7°E	15782	4810	554	O	—	—	0.25	0.9	0.28	0.9	0.6	1.8	0.42	1.3	0.32
Tenerife, Canary Is.	28°.3	16°.7W	12000	3660	645	(A)	—	—	1.1	3.4	1.2	2.2	2.3	3.7	1.9	3.7	1.4
Zelenchukskaya3)	43°50′	41°36′E	6830	2080	788	A	—	—	1.9	4.1	2.3	4.2	5.3	9.6	2.2	5.8	2.1
Mt. Ararat, Turkey	39°.7	44°.3 E	16945	5165	529	O	—	—	0.42	1.0	0.59	1.3	0.9	2.3	0.7	1.6	0.57
Mt. Everest	28°.0	87°.0 E	29002	8840	315	O	—	—	0.09	0.13	0.09	0.16	0.6	1.7	0.17	0.24	0.12

* Accessible by road (A), trail (T), not (O).

1) Point Success: summit crater unsuited.

2) Road to 15,500′ = 4730 m, where snow-covered deep cinders begin.

3) Future site of 6-meter telescope.

† These interpolated chart figures must apply to *wider* areas than the summits. (E.g., Catalina Obs. summit figures are around 40″; cf. Appendices for some other sites.)

Table IV

Antenna	Size	RMS Surface	Efficiency/λ
Lincoln Lab	28 ft.	0.2mm (.008")	55%/9mm 20%/3mm
Crimea	22m (71 ft.)	0.12mm (.005")	34%/4mm
Aerospace	15 ft.	0.05mm (.002")	54%/3mm, 20%/1.2mm
McDonald Texas	16 ft.	0.06mm (.0025")	43%/2mm, 58%/3.2mm, 26%/1.2mm
AFCRL	29 ft.	0.15mm (.006")	45%/9mm
Bonn	10m (33 ft.)	0.34mm (.014")	43%/9mm
CRC, Canada	30 ft.	0.52mm (.021")	23%/9mm
NRAO	36 ft.	0.14mm (.0055")	40%/3.2mm, 8%/1.3mm
Berkeley	20 ft.	0.15mm (.006")	∿50%/8mm
JPL, Table Mtn.	18 ft.	0.18mm (.007")	
Berkeley	20 ft.	0.10mm (.004")	