CHARACTERISTICS OF THE MILLIMETER ARRAYS

WM. J. WELCH
Radio Astronomy Laboratory
University of California
Berkeley, CA 94720

Abstract. The characteristics of millimeter wavelength arrays are discussed with a view to the general usefulness of the arrays for a wide variety of astronomical programs. Their most important capability is high angular resolution. In addition, their accurate pointing allows detailed comparison of images made at different wavelengths, and permits accurate astrometry. The existing and planned arrays have collecting areas of several hundred square meters and therefore sensitivities comparable to even the largest single reflector antennas. Because of their relative immunity to emission from the atmosphere, they are the instruments of choice for detection of weak signals from point sources. The current and planned systems have flexible correlation spectrometers with high resolution and wide spectral coverage. Their ability to accurately spatially locate emission from new spectral features is important in the identification of new molecular species. The improvement in millimeter arrays has enabled mapping with dynamic ranges of one hundred or more and good enough fidelity to permit quantitative comparison of features on different maps. Finally, large ratios of baseline length to antenna diameter yield maps with large ratios of map field size to map resolution.

1. Introduction

The development of interferometers for millimeter wavelengths began in the early 1970's after it was found that strong millimeter wavelength emission could be detected from molecules in the dust clouds in the interstellar medium, in the atmospheres of the planets, and in the envelopes of evolved stars. The high angular resolution that an interferometer could provide promised to give a glimpse of such important processes as the formation of stars in the interiors of the dense clouds. At the present time, there are five such instruments operating at millimeter or sub-millimeter wavelengths, two more that will be in operation within a few years, and another large instrument that is well along in the design and is expected to be funded for construction soon.

Single reflector telescopes have long been thought to be the more general purpose astronomical instruments. However, the millimeter arrays show that, in addition to having high angular resolution, they have many other features that are desirable for a wide range of astronomical problems. In the following paragraphs we discuss these characteristics and call attention to the capabilities of the existing and planned arrays.

2. Array Characteristics

It is well known that for high angular resolution studies arrays are necessary. A number of other, mostly related, features make them the instruments of choice for a wide range of investigations. They have inherently more accuracy in pointing, excellent sensitivity, high spectral resolution and spectral flexibility, high dynamic range in map brightness sensitivity,and large spatial dynamic range. Table 1 lists a number of the parameters of the existing (or nearly existing) systems. These parameters determine the capabilities of the instruments in these various categories.

2.1. ANGULAR RESOLUTION

The resolution achieved by an array after an earth rotation observation that adequately fills in the uv plane is approximately $0.7\lambda/s_{\rm max}$, where λ is the wavelength and $s_{\rm max}$ is the maximum baseline. Table 1 shows that the existing arrays achieve resolutions of the order one to a few arc-seconds in their operating wavelength ranges. For example, Ohashi et al. (1991), using the Nobeyama Millimeter Array, observed six embedded young stellar objects and five classical TTauri stars with resolutions of $2.8''$ to $8.8''$ in both the $\lambda 3$ mm continuum and in CS(2-1). The TTauri stars showed continuum (probably disks) and no CS, whereas the embedded stars showed, on the whole, no continuum but CS that was displaced from the IR positions, possibly core gas from which the young stars had formed.

A number of studies made with the Owens valley Millimeter Array (e.g, Sargent and Beckwith, 1987) in CO(1–0) at a resolution of $2''$ have shown flattened disk-like structures with radii of order 1000 AU surrounding T Tauri stars. Lay et al. (1994), using the CSO/JCMT sub-millimeter interferometer, found the 0.8 mm continuum emission from HL Tau to be extended, resembling a tilted disk of about 65 AU radius, and Mundy et al. (in press), with the BIMA Array, also resolved the HL Tau continuum at $\lambda 2.7\,$mm finding a similar structure. Interferometric resolutions of a few arc-seconds or better were essential to all of these studies.

2.2. ACCURATE ANGULAR REGISTRATION

Arrays enjoy a substantial advantage over single reflector telescopes in pointing accuracy. The IRAM 30 m telescope has an angular resolution approaching that of the arrays when it is operated at its shortest wavelength of about one millimeter. However, pointing of this telescope, like other single reflectors, to better than one or two arc-seconds is very difficult. The arrays, on the other hand, routinely point to a fraction of an arc second. One reason is mechanical. The array elements are fastened to the ground, a much stiffer structure than the relatively floppy backup frame of a single reflector. The other reason is that the array is relatively immune to the refractive effects of the atmosphere. The array elements are fastened to the ground, and, to the extent that the atmosphere is a plane layer, the ray paths through the atmosphere are the same to every element independent of source elevation.

Maps, such as those of the T Tauri stars discussed above, have typical pointing accuracies of one arc-second or better, which is helpful for comparison with images made at other wavelengths. With care, pointing to 0.1 arc-second or better is possible. For example, Wright et al. (1990) and Baudry et al. (1995) have measured the positions of SiO masers in a number of Red Giant Stars to accuracies of about $0.1 - 0.2''$. Table 2 shows the results of Baudry et al. (1995) for 13 stars. The agreement with the optical astrometry of the stars is quite good.

2.3. SENSITIVITY

The instantaneous sensitivity of an array is proportional to its collecting area, and, if the extent of the observed source fits within the primary beam of the array antennas so that only a single pointing of the array antennas is needed, the brightness sensitivity in the synthesized map is also just proportional to the total collecting area. This number is given for the existing arrays in column 4 of Table 1. For the bigger arrays, it is quite comparable to the collecting areas of the biggest single millimeter dishes. Because the cost of individual millimeter receivers is now modest, it is less expensive to build up the collecting area in an array of antennas rather than in a single large reflector. The excellent sensitivity of arrays is illustrated by the detection of CO (1-0) emission from the QSO 3c48 at $z = 0.3695$ with the earlier three element OVRO array shown in Figure 1 (Scoville et al., 1993) and the map of IRAS 10214+4724 with the IRAM array (Radford et al., 1993).

If the source size is larger than the primary beam of the interferometer elements so that multiple pointings must be used, then the dependence of array brightness sensitivity on antenna diameter is linear rather than quadratic. This is shown for the existing arrays in column 5 of Table 1. Whereas the point source sensitivities vary over a factor of three among the arrays, it is roughly the same for all the arrays in the multiple pointing case. The bigger antenna systems are more suited for the small sources and the smaller antenna systems are better used for the more extended sources. The planned MMA is a compromise between these two sensitivities.

2.4. SPECTRAL RESOLUTION AND FLEXIBILITY

The spectrometer for an array, which is also the correlator for $n(n-1)/2$ baseline pairs, is a much bigger electronic component than the corresponding unit for a single reflector telescope. However, its cost relative to that of the antennas is small for almost any sized array, and the units that have been built for all the existing arrays are comparable to the spectrometers of the single reflector antennas. Typically, they have best resolutions of a few kHz, maximum bandwidths of several hundred, up to 1000, MHz, and the ability to observe several spectral lines at the same time in multiple windows. The arrays enjoy a perhaps surprising advantage for interstellar chemistry studies apart from their flexible spectral correlators. From an array observation one gets maps as well as several spectra. The molecular chemistry differs among clouds(e.g., Snyder et al., 1992), and if a new species is being identified by a number of emission spectra, it is important to be certain that all the candidate lines arise from the same cloud.

2.5. DYNAMIC RANGE IN BRIGHTNESS

The dynamic range in brightness in array maps depends on such factors as stability of the array electronics, pointing, completeness of the uv coverage, and, most importantly, the basic sensitivity of the system. As the stability of the millimeter systems has improved and the number of antennas has increased, the existing arrays have been producing maps of ever greater dynamic range and fidelity, gradually approaching the quality of maps made with the centimeter wave arrays, such as the VLA. An example is shown in Figure 2, a continuum map of the HII region complex W49 at 87 GHz done with the BIMA array (Wilner et al., in preparation). In addition to array data, this map contains single antenna data taken with the IRAM 30 m antenna, so that it is complete over all scales up to the interferometer primary beam of $120''$. It is a single pointing map. The peak flux is about 100 times the noise level, giving a dynamic range of 100. Comparison with a VLA map at 6 cm suggests an accuracy of the map features of about 10%, for a fidelity of 10. Since this is the array with the least collecting area in Table 1, we can expect even better results with the arrays with greater collecting area.

2.6. SPATIAL DYNAMIC RANGE

Spatial Dynamic Range is used here to mean the ratio between the size of the field and the synthesized beam. For a single pointing of the array antennas, this ratio will be close to the ratio of the longest baseline used to the array antenna diameter. This parameter is shown in the last column of Table 1. For multiple pointing observations this dynamic range can, of course, be increased. Figure 2 is also a good example of a field observed with a large dynamic range. The primary beam is $120''$ and the synthesized beam is about $0.6''$ for a ratio of 200. An inspection of Table 1 shows the complementarity between the various arrays. Part of the large spatial dynamic range of the BIMA array comes at the expense of having a smaller array antenna with corresponding lower collecting area. The MMA has clearly been planned to study complex fields and is a compromise between point source sensitivity and good imaging capability.

3. Future Developments

The future will bring further developments with the existing arrays and the construction of new arrays which are being planned.

3.1. MILLIMETER WAVELENGTH SEEING

A number of studies have shown that the interferometer phase fluctuations caused by atmospheric turbulence increase roughly monotonically with baseline for kilometer scale baselines with $\sigma_\phi \sim s^{0.7}$ (Sramek, 1990; Wright and Welch, 1990; Olmi and Downes, 1992). Since a maximum array spacing of a given length yields a map with a resolution inversely proportional to wavelength, the above power law implies that, on the average, the attainable resolution increases with wavelength. The resolution is poorer at millimeter wavelengths. Olmi and Downes (1992) find a median seeing of about $2''$ at one millimeter wavelength. Imaging of better than one arcsecond will only be possible in exceptional weather.

At the present time, several groups are developing calibration schemes based on the idea that the atmospheric water vapor that produces the phase fluctuations also should produce fluctuating emission at millimeter wavelengths, especially near the water vapor absorption wavelengths. Thus, a measurement of the fluctuation in the brightness of the atmosphere will permit the correction of the phase fluctuation (cf Welch, 1994). It appears that one or all of the schemes will probably work. The correction will not only allow observations at sub-arc-seconds much of the time, but it will also permit elimination of the atmospheric de-correlation that is present in observations most of the time at shorter spacings. More accurate imaging should be the result.

3.2. NEW INSTRUMENTS

In addition to the MMA of the NRAO included in Table 1, there are two more arrays being planned. One is a large array for both millimeter and sub-millimeter wavelengths proposed by the NRO. The second is an array with an order of magnitude more collecting area than the MMA. These will allow the milliarc-second resolution that will resolve molecular clouds in the most distant galaxies and that may be necessary to fully understand the formation of stars.

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References

Baudry, A., Lucas, R., and Guilloteau, S. 1995, *A&A*, **293**, 594.
Lay, O. P., Carlstrom, J. E., Hills, R. J., and Phillips, T. G. 1994, *ApJ*, **434**, L75.
Ohashi, N., Kawabe, R., Hayashi, M., and Ishiguro, M. 1991, *A. J.*, **102**, 2054.
Olmi, L., and Downes, D. 1992, *A&A*, **262**, 634.
Radford, S. J. E., Brown, R. L., and Vanden Bout, P. A. 1993, *A&A*, **271**, L21.
Sargent, A. I., and Beckwith, S. V. W. 1987, *ApJ*, **323**,294.
Sargent, A. I. and Welch, W. J. 1993, Ann. Rev. *A&A*, **31**, 297.
Scoville, N. Z., Padin, S., Sanders, S., Soifer, B. T., and Yun, M. S. 1993, *ApJ*, **415**, L75.
Snyder, L. E., Hollis, J. M., Ziurys, L. M. and Kuan, Y. J. 1992, in *IAU Symposium 150: The Astrochemistry of Cosmic Phenomena*, ed. P. D. Singh (Dordrecht: Kluwer), 187.
Sramek, R. A. 1990, in *IAU/URSI Symposium on Radio Astronomical Seeing*, eds. J. E. Baldwin and Wang Shouguan, 21.
Welch, W. J. 1994, in *IAU/URSI Colloquium 140: Astronomy with Millimeter and Sub-Millimeter Interferometers*, eds. M. Ishiguro and W. J. Welch
Wright, M. C. H., Carlstrom, J. E., Plambeck, R. L., and Welch, W. J. 1990, *A. J.*, **99(4)**, 1299.
Wright, M. C. H., and Welch, W. J. 1990, *IAU/URSI Symposium on Radio Astronomical Seeing*, eds. J. E. Baldwin and Wang Shouguan, 71.

TABLE 1. Properties of the Millimeter Arrays

Array	n	D [m]	$n\frac{\pi}{4}D^2$ [m^2]	nD [m]	Wavelength [mm]	Baseline EW/NS [m]	$s_{\rm max}/D$
IRAM	5	15	883	75	$\lambda 1, 3$	430/240	33
BIMA	10	6	283	60	$\lambda 1, 3$	1000/1000	200
CSO/JCMT	2	10/15	212	—	$\lambda 0.3 - 1.0$	165	14
NRO	6	10	471	60	$\lambda 1, 2, 3$	560/520	60
OVRO	6	10.4	509	63	$\lambda 1, 3$	200/220	29
AT	5	15	883	75	≥ 2.6	3000(EW)	136
SMA	8	6	226	48	$\lambda 0.3 - 1.3$	800/800	133
MMA	40	8	2000	320	$\lambda 0.9 - 9.0$	3000(Circ)	375

NOTE: IRAM is Institute de Radio Astronomie Millimetrique; BIMA is Berkeley-Illinois-Maryland-Association; CSO is Caltech Sub-millimeter Observatory; JCMT is James Clerk Maxwell Telescope; NRO is Nobeyama Radio Observatory; OVRO is Owens Valley Radio Observatory; AT is Australia Telescope; SMA is Sub-millimeter Array (Harvard/SAO); MMA is Millimeter Array(NRAO). (Sargent and Welch, 1993)

TABLE 2. Positions of SiO Maser Stars (from Baudry et al., 1995)

Star	Mean epoch	α (2000.0) [h m s]	δ (2000.0) [° ′ ″]	$V_{\rm LSR}$ [km s^{-1}]		Estimated errors σ_α[″]	σ_δ[″]
o Ceti	1992.04	02 19 20.797	*	44,	46.5	0.20	*
S Per	1991.33	02 22 51.713	58 35 11.50	−40,	−38	0.20	0.20
TX Cam	1992.04	05 00 51.127	56 10 53.98	6,	9.5	0.15	0.15
Ori IRc2	1992.05	05 35 14.498	−05 22 30.70	14.5,	18	0.15	0.20
U Ori	1992.04	05 55 49.171	20 10 30.34	−42,	−39	0.15	0.25
R Cnc	1991.32	08 16 33.826	11 43 34.60	11,	17	0.10	0.15
R Leo	1991.33	09 47 33.490	11 25 43.99	−5,	−1	0.10	0.15
RX Boo	1992.03	14 24 11.609	25 42 13.73	−1,	8	0.10	0.20
RU Her	1992.05	16 10 14.519	25 04 14.41	−13,	−6	0.15	0.15
VX Sgr	1991.32	18 08 04.062	−22 13 27.30	−2,	11	0.20	0.25
NML Cyg	1992.05	20 46 25.532	40 06 59.35	−10,	−4	0.15	0.15
μ Cep	1991.33	21 43 30.446	58 46 48.40	24,	29	0.20	0.15
R Peg	1992.03	23 06 39.157	10 32 36.07	22,	26	0.15	0.20
R Cas	1991.33	23 58 24.781	51 23 19.10*	21,	28	0.20	*

* The declination uncertainty was not reliably estimated.

Figure 1. Spectrum of the CO emission from the radio-loud quasar 3C48 observed with the OVRO Millimeter Interferometer.

Figure 2. Map of the giant HII region W49A made with the BIMA array (Wilner et al, in preparation) at 87 GHz. Resolution is $0.6''$, and total flux from the IRAM 30 m is included. The peak is 100 times the RMS noise level.