Imaging Distant Dust and Gas: The Millimeter Array

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Abstract. Although the richness of the millimeter/submillimeter sky has been known for the last two decades, precision imaging of the sky has been impossible at all but the longest wavelengths. The Millimeter Array (MMA) will consist of 36 precision 10m antennas located above 5000m altitude in the Atacama Desert of Chile. It will apply aperture synthesis techniques for precision imaging of the cool thermal sky, particularly those objects which can now only be studied in the far infared with coarse angular resolution. The MMA will offer unprecedented sensitivity–it will image a galaxy with the dust mass of the Milky Way at z=1 in one minute. The images the MMA will produce of this and high z systems will be high resolution images: the MMA will offer unprecedented angular resolution for imaging cool matter, providing images at a few hundredths arcsecond resolution. The MMA provides extinction-free spectroscopy of dusty high z systems. The MMA is currently under development; construction is scheduled to begin in 2001 with operations scheduled to begin in 2008.

INTRODUCTION

The Millimeter Array (MMA) is a millimeter wavelength telescope funded for design and development by the National Science Foundation during 1998-2001. The MMA design specifications include:

- Thirty-six 10-meter antennas on the 16400 foot elevation Llano Chajnantor, Chile
- Imaging instrument in all atmospheric windows between 10 mm and 350 μm
- Spatial resolution of 10 milliarcseconds, 10 times better than the VLA or the Hubble Space Telescope
- Velocity resolution under 1 km/sec
- Array configurations from approximately 80 meters to 10 km
- Able to image sources arcminutes to degrees across at one arcsecond resolution

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[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

• By more than an order of magnitude the largest and most sensitive instrument in the world at millimeter and submillimeter wavelengths

During the 1980s, astronomers identified millimeter arrays as a goal for instrumental development. Caltech and Berkeley operated and upgraded their facilities, the Smithsonian Institution entered a design and development phase for their Submillimeter Array on Mauna Kea, while NRAO planned for a national facility, the Millimeter Array (MMA), submitting a proposal to NSF in 1990. In 1991, the Astronomy and Astrophysics Survey Committee of the National Research Council identified the Millimeter Array as one of the highest priority telescope programs to be undertaken in the 1990s. Funding for the Design and Development Phase of the MMA began 1 June 1998. This phase is expected to continue at NRAO, BIMA and OVRO through 1 June 2001. Construction of the MMA is expected to commence in FY2000 at Llano Chajnantor, Chile. This phase will culminate with operation at the end of 2007 or early 2008.

Other countries have also identified a large millimeter array as national priorities for astronomical instrumentation. In Europe ESO, IRAM, NfRA, MPIfR and OSO along with the UK have studied a Large Southern Array, or LSA, with much larger collecting area than the MMA proposed. An agreement between ESO, France, the UK and others is being pursued with a goal of synchronizing a development phase of the LSA with that of the MMA. In Japan, astronomers have planned a Large Millimeter and Submillimeter Array (LMSA) of intermediate collecting area. As a result, the possibility of merging the instruments into a Large Millimeter Array, or LMA, is being pursued and will be the focus of an URSI workshop in Toronto in August 1999.

THE SITE

The location of the 16400 foot Cerro Chajnantor site is just south of the road from the mining town of Calama in northern Chile as it extends toward the Paso de Jama into Chile. With only 10cm of rain a year, this is one of Earth's driest regions. Extensive site testing has shown it to be drier, with a more stable atmosphere, than Mauna Kea. Less than one millimeter of precipitable water lies above the site for half each year (day plus night, winter plus summer), resulting in an optical depth in the critical submillimeter windows of about one or less for much of the time. Nearby at 8000 foot elevation lies the charming ancient town of San Pedro de Atacama, whose water supply has drawn visitors since Inca times. A tourist town, it is a starting point for expeditions to nearby geysers, salt lakes and volcanoes as well as the Inca ruins. It will become a center of MMA operations.

Operation at such a superb site as Llano Chajnantor, the large collecting area of the array (up to a factor of ten for the LMA), its planned large bandwidth (16 GHz as compared to 1 GHz on existing arrays), antennas and receivers optimized for operation on the excellent site, and the long baselines available on the site will provide sensitivity improvement measured in orders of magnitude over presently operating or planned millimeter or submillimeter instrumentation. Currently, the weakest sources in these bands which have ever been detected measure about one millijansky in flux. With the MMA, this sensitivity will be reached in less than one second. Since thermal science is the target of the array, good brightness temperature sensitivity is critical to the array. Even on the longest baselines, the array will offer sufficient sensitivity to, for example, image CO emission from the Milky Way Galaxy to beyond z=1. High sensitivity without sufficient spatial resolution can result in confusion by weak unresolved sources. The MMA brings to the submillimeter regime the precision imaging capability of the VLA, HST, Keck or Gemini, providing resolution of 0.05″or better. While confusion will limit the usable sensitivity of other submillimeter instruments, such as JCMT/SCUBA, CSO/SHARC, FIRST, SOFIA, Planck Surveyor or BOLOCAM, **the MMA will execute extremely deep galaxy surveys without reaching the confusion limit** (Blain, Ivison and Smail 1998) [1].

CONTINUUM OBSERVATIONS

The distinct nature of the submillimeter sky is nicely demonstrated by comparison of the Hubble Deep Field (HDF) in optical (and radio by Richards et al. 1998 [2]) and in submillimeter (SCUBA 850μm by Hughes et al. 1998 [3]). Rapidly increasing volume with redshift combined with strong K-correction ($S_\nu \propto \nu^{3-4}$) means that the brightest sources at submillimeter wavelengths are the distant (z>1) dusty galaxies. Higher star formation rates in the earlier epochs [4] adds to the dominance of high redshift objects in the submillimeter.

Comparison of the expected blackbody spectrum of the ultraluminous starburst galaxy Arp 220 as seen at high redshifts with the frequency coverage and the sensitivity of the MMA suggests that The Millimeter Array should be able to detect Arp 220-like dusty starburst galaxies out to a redshift of 10 or more. Galaxies like the present day Milky Way can also be detected out to z beyond 1.

Predicted detection rates for mm/submillimeter sources by the existing and future instruments at 5 sigma significance have been calculated by Blain 1998 [5]. The expected detection speed of the MMA is about 100 times faster than the current SCUBA and comparable to that of the BOLOCAM when installed in the future LMT (Olmi and Mauskopf 1998) [6], without suffering from confusion.

SPECTROSCOPIC OBSERVATIONS

Along with the dust continuum emission, various redshifted spectral lines such as all rotational transitions of CO and infrared fine structure lines such as [C II] and [O I] can be detected and studied to derive the molecular gas content and star forming activity. Secure detections of redshifted CO lines from dusty galaxies at cosmological distances already exist (e.g. z=2.3 FSC 10214+4724 [Brown & Vanden Bout 1992] [7], z=4.7 BR 1202-07 [Ohta et al. 1996 [8], Omont et al. 1996] [9]) and z=2.6 H1413+117(e.g. Barvainis et al 1997) [10], among others. The search for CO emission from luminous submillimeter galaxies identified by deep SCUBA surveys are also underway, and the detection of CO (3-2) emission in the z=2.8 submillimeter galaxy SMM02399-0136 was reported recently. **The high frequency resolution attained with the MMA, enabling dynamical studies of distant objects, is a capability unmatched by other observatories planned for the next decade, such as NGST, SIRTF**.

The Spectral Energy Distribution (SED) of the first luminous submillimeter galaxy detected by SCUBA, SMM02399-0136 at z=2.8 (Ivison et al. 1998) [11] is essentially identical to the z=2.3 hyperluminous infrared galaxy FSC 10214+4724 and has the same shape, dominated by the FIR/submillimeter peak, as in the prototype ultraluminous galaxy Arp 220. The apparent luminosity is about 100 times larger however, partly due to gravitational magnification by a foreground cluster.

Redshifted CO (3-2) emission from the z=2.8 submillimeter galaxy SMM02399-0136 is detected and mapped using the Caltech millimeter array by Frayer et al. (1998) [12], confirming the optical identification of the distant faint optical galaxy as the submillimeter continuum source. The CO spectrum obtained measures the redshift of the host galaxy to be z=2.808, coincident with the optical galaxy within the uncertainty of registering the optical HST image.

Although detection of the CO emission from SMM02399-0136 required about 40 hours of observation with OVRO, such a 6 mJy line should be detected to about 3σ in one minute with the MMA with a velocity resolution of 25 km s^{-1}; owing to the larger MMA bandwidth, offsets between molecular and optical redshifts will not compromise the ability to detect a galaxy in molecular line emission.

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