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The Future Large Millimeter and Submillimeter Array (LMSA/ALMA) Project

By

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Abstract: The Japanese Large Millimeter and Submillimeter Array (LMSA) and the US/Europe Atacama Large Millimeter Array (ALMA) are planned to be constructed at a very high and dry site in the northern Chile and to be operated at the frequency range of 80 to 900 GHz from around the year of 2008. LMSA (or ALMA) will provide 0.01 arcsecond resolution and a very high sensitivity comparable to a 70 m single dish. Their main targets include planetary system formation and galaxy formation/evolution. Big advances in other researches (e.g., cosmology) are also expected. The technical challenges to key instruments for such arrays are now being tackled. The international collaboration toward a so-called "enhanced ALMA" (an unified array of LMSA and ALMA) is under discussion.

1. INTRODUCTION TO LMSA/ALMA

1.1 Scientific Motivations for Large millimeter and Submillimeter Arrays

The observations of cool interstellar material, from which planets, stars, and galaxies are formed, in the millimeter and sub-millimeter wavelength ranges during the past 20 years have helped to elucidate the nature and evolution of interstellar matter in the Galaxy and external galaxies. The observations also revealed various exciting phenomena such as active outflows from and mass accretion onto newly formed stars, protoplanetary disks of dust and gas around young stars, and formation of galaxies in the early universe (e.g. Kawabe et al. 1993, Ohta et al. 1996). These studies have led great progress in understanding the process of star and planet formation, the evolution of galaxies, and interstellar chemistry.

The Large Millimeter and Submillimeter Array (LMSA) project (Ishiguro et al. 1998, see also http://www.nro.nao.ac.jp/~lmsa/) of the Japanese astronomical community entails the construction of an interferometer consisting of fifty 10m-class antennas (recently changed to 32×12 m antennas) and covering the frequency range of 80 GHz to 900 GHz. With a maximum baseline of 10 km, spatial resolution of 0.01 arcsecond could be achieved for the observations

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Fig. 1: Artist's impression of the Large Millimeter and Submillimeter Array (LMSA).

at 300 GHz. A similar array, Atacama Large Millimeter Array (ALMA; 64 × 12 m antennas), is planned by US and Europe (see http://www.mma.nrao.edu/, http://pupis.ls.eso.org/lsa/lsahome.html). A breakthrough is expected by combining these into a more capable and powerful array. The unprecedented high sensitivity (see Figure 2) and high spatial resolution provided by LMSA/ALMA will open a new era in the millimeter and submillimeter astronomy. Such an array will be a powerful tool to explore a great variety of important astronomical problems of current interest, such as formation of planetary systems, and formation of galaxies.

1.2 Specifications of LMSA/ALMA

The spatial resolution achieved is as high as 0.01 arcsecond even for thermal emission such as dust and molecular emission. This is 10 times finer than that achieved by the world's largest optical/infrared telescopes such as Hubble Space Telescope or SUBARU 8.3 m telescope. The maximum angular resolution corresponds to 1.4 AU (Astronomical Unit) at the distance of the Taurus dark cloud. The structure of protoplanetary disks could be resolved and the central planet forming regions could be investigated with this high resolution (see Figure 3).

The collecting area of each of LMSA/ALMA is about 8000-10000 m^2, which corresponds to a 70 - 80 m single dish telescope. Each antenna for LMSA is planned to be equipped with highly sensitive receivers using SIS (superconductor-insulator-superconductor) junction and super-conducting tunnel junctions, which covers the entire atmospheric windows in the short-millimeter and submillimeter wavelengths shown in Figure 6 (Takagi & Arimoto 1997). The high sensitivity achieved by the large collecting area and sensitive receivers would allow us to search for galaxies forming in the very early universe (see Figure 2), which are shrouded by dusty clouds, and are, therefore, difficult to be detected by optical and IR observations. The huge number of baselines (i.e., Fourier components; 1225 for LMSA) can be obtained at a time, and high-quality imaging can be performed even with so-called snap shot observations.

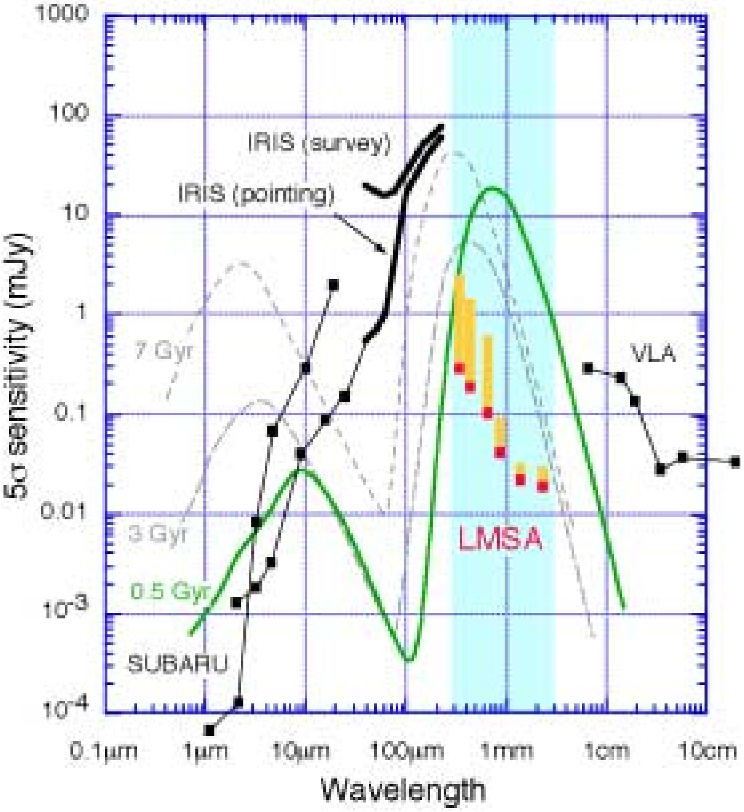

Fig. 2: Sensitivities of LMSA (bottom square for mostly the best atmospheric condition and top for the average condition) and other major astronomical instruments overlaid on theoretical spectral energy distributions of a medium-sized (10^{11} $M_\odot$) young elliptical galaxy in its different stages of evolution (0.5, 3, and 7 Gyr after its formation) (Takagi & Arimoto 1997). Assumed integration time is 8 hr for LMSA and VLA while it is 1 hr for SUBARU. Note that, because of the positive effect of redshift, younger galaxies in deep universe are brighter in millimeter and submillimeter wavelengths while in optical and infrared wavelengths they are dimmer and thus are easily contaminated by less massive evolved galaxies in nearby universe.

2. THE SITE

In 1990, we started the site survey for the LMSA over the world; e.g., in northern Chile, India, and China. The specifications of good sites are (1) high atmospheric transparency and good seeing at submillimeter wavelengths, (2) a flat and wide ($> 3 \times 3$ km) area, (3) low velocity wind for accurate pointing of the antenna, (4) easy accessibility, and so on.

After a preliminary examination of the meteorological and other data, we started in 1992 our first site survey activity for the LMSA in northern Chile in collaborations with the European Southern Observatory and the University of Chile. In July 1995, we installed a 220 GHz tipping radiometer and an 11 GHz radio seeing monitor (an interferometer receiving a geostationary satellite signal) at Rio Frio (4100 m). The same set of equipments was also installed in 1996 at Pampa la Bola (Figures 4 & 5). By comparing the atmospheric conditions and also the

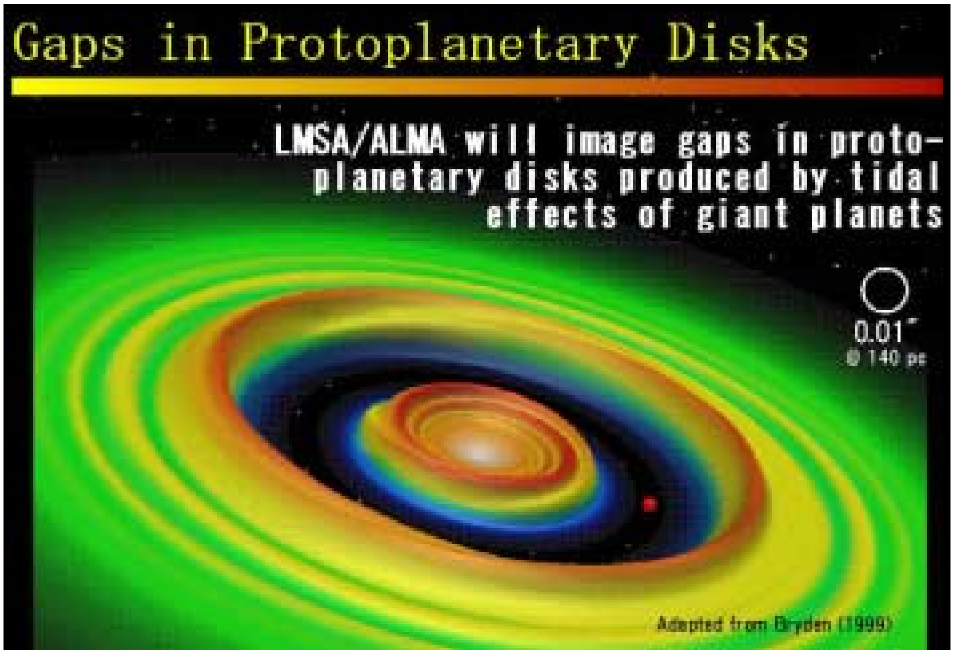

Fig. 3: Gap in the protoplanetary disk produced by the formation of a Jupiter-like planet (results of computer simulation), which will be able to be imaged by LMSA/ALMA.

accessibility, we decided the Pampa la Bola-Chajnantor region as the candidate site of LMSA. This region is one of the most excellent sites for the submillimeter observations as shown in Figure 6 (Takagi & Arimoto 1997).

3. TECHNICAL CHALLENGES TO KEY INSTRUMENTS

3.1 Key Instruments

The key instruments of LMSA/ALMA are 1) a high-precision submillimeter antenna, 2) low-noise millimeter and submillimeter receiver systems, 3) a very wide-band spectro-correlator which can handle huge data set from a large number of antennas, and 4) a radiometric system for atmospheric phase correction in order to achieve high spatial resolution by active correction of the phase. The research and developments for these key items have been performed for more than two years in Japan. Recently, we started the design and construction of prototypes of such instruments as antenna, receivers, and correlators, as described in the following subsections.

3.2 High Precision Sub-mm Antenna

The design of the high-precision antenna for LMSA/ALMA needs extreme care. This is because it is the first time a 10 m class antenna is being developed fro use in the exposed condition and because replacing or upgrading a number of high-precision antennas constructed and installed will be quite costly. The design of the element antennas is, therefore, one of the key issues in the research and development phase. For the Japanese design and development, we constructed a 10 m prototype antenna at Nobeyama in Japan as shown in Figure 7 (Ezawa et al. 2000, Ukita et al. 2000). We designed the antenna by considering the following aspects: 1) good

Fig. 4: Locations of a candidate LMSA site, Pampa la Bola in northern Chile, which is only a few kilometers apart from the paved international highway from Chile to Argentina and several kilometers north from Chajnantor (ALMA site).

antenna performance for observations up to 900 GHz, 2) easy assembling at the site with an altitude of about 4800–5000m, easy maintenance (or inspection) and high reliability under the environmental condition, 3) good matching with scientific requirements.

The specifications of the prototype were defined as follows. The maximum surface error was set to ~1/20 of the shortest observing wavelength (340 μm), 10% of the field-of-view at 340 μm. Maximum slue rate was set to enable fast switching calibration. This prototype antenna will be moved to the LMSA construction site in Chile for evaluation in the 345–810 GHz range in 2001.

3.3 Sub-mm Mixers and Refrigerators

Receivers for the six atmospheric windows from 80 (or 30) to 890 GHz are planned for each antenna of LMSA/ALMA, as noted in the caption of Figure 6. Mixers using SIS tunneling junction will be adopted for most of these bands. The receiver noise temperature required for LMSA/ALMA is just a few times the quantum noise limit at each frequency band (Sekeimoto et al. 2000).

Recently, novel types of Nb-based SIS junctions called PCTJ (Parallel Connected Twin

Fig. 5: Site testing instruments and containers at the 4800 m site of Pampa la Bola, Region II, Chile. Two containers equipped with solar panels and one of the antennas of the radio seeing monitor can be seen in the background. Three weather stations under cross calibration are seen in the foreground.

Junction) and "Distributed Junctions" have been developed at NRO (Shi, Noguchi, & Inatani 1997). PCTJ is now used for receivers at frequencies up to 500 GHz and an excellent performance has been demonstrated as shown in Figure 8. An SIS receiver, covering a frequency range of 80-345 GHz with three mixers, was constructed and is under test on the prototype antenna. An LMSA prototype receiver, covering the range of 80 GHz to 890 GHz, is now under development and will soon be installed in the prototype antenna for the test in Chile (Sekeimoto et al. 2000).

Mass production of state-of-the-art mixers, one of the important items for the LMSA receiver development, are now being tested for a 25-beam 100 GHz receiver on the NRO 45 m telescope. In addition, the development of NbN-based SIS mixers at a terahertz range, an SIS photon detector array, a 492 GHz SIS receiver and also the evaluation of the stability of a 4 K cryocooler have been conducted by universities and the NRO under the frameworks of the LMSA collaborative development.

To date, heterodyne detectors based on SIS junctions have used local oscillators (LO's) consisting of frequency multipliers and diode oscillators. An alternative LO system is photonic LO sources, i.e., photodiode or photomixer which generates the difference frequency of two laser diodes by optical heterodyne conversion. Photonic LO may reduce the mechanical complexity and improve the frequency coverage especially at submillimeter wavelengths. Several types of photonic LO (or laser heterodyne systems) have been proposed and tested so far. One of the most promising photonic LO sources in the near future is an InP-InGaAs uni-traveling-carrier (UTC) photodiode developed by (Shimizu et al. 1998a, b). The output power of this source is expected to be about 1 mW at 150 GHz. The other one is low-temperature-grown (LTG) GaAs developed by (Matsuura et al. 1999).The output power of 0.1 mW was obtained at 800 GHz and this photomixer LO was used for the 630 GHz SIS receiver (Verghese et al. 1999). The development of sub-mm photonic LOs is underway in NRO in collaboration with NTT and National Radio Astronomy Observatory (NRAO).

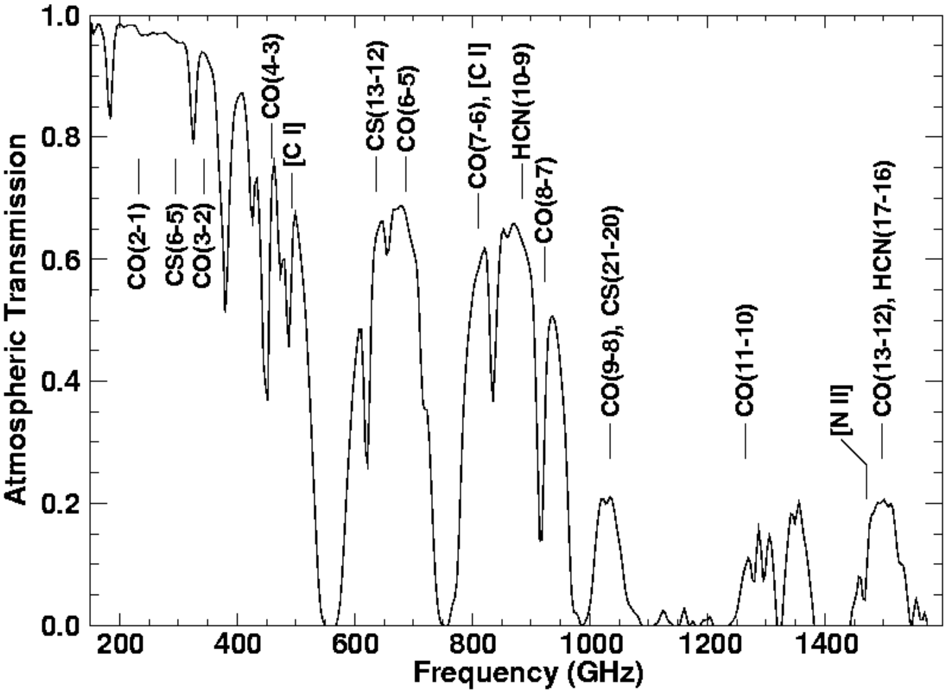

Fig. 6: Best atmospheric transmission measured at the 4800 m site of Pampa la Bola, Region II, Chile, measured with a Fourier-transform spectrometer (Takagi & Arimoto 1997) and important interstellar molecular and atomic lines in short millimeter and sub-millimeter wavelengths. Note that super-terahertz atmospheric windows around 1, 1.3, and 1.5 THz were clearly identified as well as the 650 and 850 GHz windows with the peak transmission of > 60%. The receiver bands proposed for LMSA in order to cover the atmospheric sub-millimeter windows up to 900 GHz are 80-140, 130-200, 200-310, 330-420, 390-500, 630-710, and 800-890 GHz.

3.4 Wide-band Digital Spectro-correlator

There are three technical requirements for the correlator system in LMSA/ALMA. One is a wider observing bandwidth for achieving very high sensitivity in continuum observations. The other two are high spectral (frequency) resolution for the detailed study of kinematics and a number of correlations to handle the large number of cross-correlations produced by a large number of antennas. There are basically two different types of digital correlators, so-called FX and XF, which being are considered as a spectro-correlator for the LMSA or ALMA, in order to achieve such requirements.

The FX type correlator performs Fourier transform action (F) before cross-correlation (X). This correlator is thought to fit well to LMSA or ALMA (or the future unified single array) which should handle a large number of correlations and simultaneously cover wide band with very high spectral resolution (i.e., a huge number of spectral channels) (Chikada et al. 1987). The current specifications of the FX correlator for LMSA/ALMA are 1) a bandwidth of more than 4 GHz, 2) number of spectral channels per correlation (baseline) of 128 × 1024, and 3) correlations of more than 2016 (produced by 64 antennas).

The prototypes of the FX correlator and very high-speed sampler are now under devel-

Fig. 7: LMSA prototype antenna constructed at Nobeyama Radio Observatory (NRO).

opment (Okumura, Chikada, & Momose 2000). The sampler is used for the analog to digital conversion of the IF signal before the Fourier transform action, and one of key components for achieving wide observing bandwidth. The sampling rate of the prototype is as high as 4G sample/sec. (Gsps) and the prototype FX, therefore, has an observing bandwidth of 2 GHz and a number of frequency channels, 128×10^3. The design study of the prototypes is mostly finished and the prototype correlator and sampler will be tested in the year of 2001.

4. International Collaboration

There is an international consensus on the scientific importance of a large array in millimeter and submillimeter wavelengths, and projects similar to the LMSA have been planned also in the United States and in Europe. The National Radio Astronomy Observatory (NRAO) of the United States proposed the Millimeter Array (MMA) project (http://www.mma.nrao.edu/), whereas the European Southern Observatory (ESO) proposed the Large Southern Array (LSA) project (http://pupis.ls.eso.org/lsa/lsahome.html). The original designs of the MMA and the LSA were forty 8 m antennas and fifty 15 m antennas, respectively, both operating in the millimeter wavelength. The MMA and LSA projects were later merged into a single project called "Atacama Large Millimeter Array (ALMA)", which consists of sixty-four 12 m antennas.

Since both LMSA and ALMA projects are planned to be constructed in the Pampa la Bola-Chajnantor area, a breakthrough is expected by combining these arrays into a more capable array. Design and development activities of these three parties are coordinated toward an "Enhanced ALMA", i.e., a unified array of LMSA and ALMA.

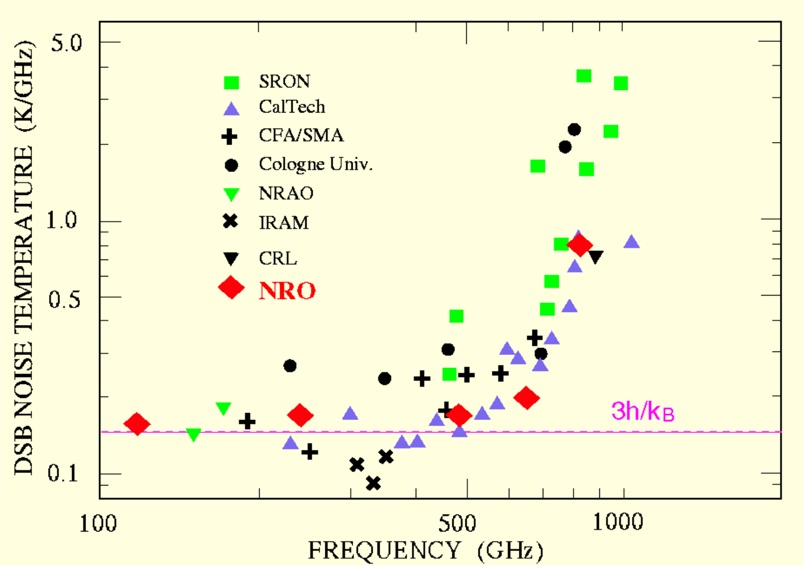

Fig. 8: DSB receiver noise temperatures normalized by measured (LO) frequencies in GHz for receivers developed in Nobeyama Radio Observatory (NRO) and the other institutes in the world.

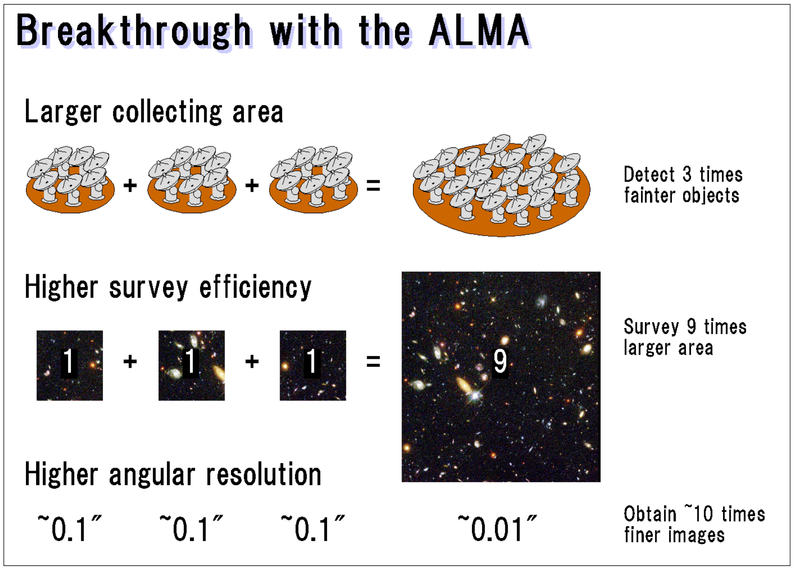

Fig. 9: Benefit of combining the three same-size array project, LMSA, LSA, and MMA.

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