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THE LARGE MILLIMETRE TELESCOPE (LMT)[1]: TRACING THE EVOLUTION OF STRUCTURE IN THE EARLY UNIVERSE

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RESUMEN

El Gran Telescopio Milimétrico (GTM), está llegando a su etapa final de construcción. Presento la situación actual del proyecto del GTM, incluyendo los planes de puesta en operación de dos de los intrumentos de primera luz (AzTEC y SPEED) en otros telescopios sub-milimétricos. Las capacidades propuestas para el GTM y la estabilidad atmosférica y transparencia sobre el sitio en el Volcán Sierra Negra (México), en combinación con la calidad de la instrumentación del GTM brindarán gran velocidad de mapeo y alta resolución angular para un telescopio milimétrico de un solo plato. Una de las metas científicas primarias del GTM, la medición de la formación y evolución de la estructura extragaláctica en el Universo sobre un amplio intervalo de escalas físicas, se beneficiará de estas ventajas.

ABSTRACT

The Large Millimetre Telescope (LMT), or Gran Telescopio Milimétrico (GTM), is approaching the final stage of construction, and the fabrication and installation of the surface panels will begin shortly. In this paper the current status of the LMT project is summarised, including the plans to commission two of the first-light LMT instruments (AzTEC and SPEED) on other (sub-)millimetre telescopes. The designed capabilities of the LMT and the atmospheric stability and transparency above the observing site on Volcán Sierra Negra (Mexico), combined with the performance of the suite of LMT instrumentation will provide very fast mapping-speeds and high-angular resolution for a single-dish millimetre-wavelength telescope. One of the primary scientific goals of the LMT, namely to measure the formation and evolution of extragalactic structure in the Universe over a wide-range of physical-scales, will exploit these advantages. Examples of cosmological millimetre-wavelength surveys that will trace the large-scale distribution of high-redshift optically-obscured starburst galaxies and anistropies in the CMB induced by massive clusters are presented.

Key Words: **COSMOLOGY — GALAXIES: CLUSTERS — GALAXIES: EVOLUTION**

1. INTRODUCTION

Technological advances during the last decade have enabled bolometer cameras to contribute sub-millimetre and millimetre-wavelength (hereafter sub-mm) continuum data to some of the most exciting results in observational cosmology (e.g. the measurement of the geometry and matter content of the Universe, and the evidence for dark energy). Important and challenging questions however remain unanswered. For example, the hierarchical model of structure formation implies that the largest-structures (e.g. coherent filaments and simple over-densities) in the universe form from initial fluctuations in the underlying dark-matter distribution which evolve rapidly and dynamically under the influence of gravity until suppressed by the dominance of dark energy at $z < 1$. The spatial (i.e. angular and redshift) distribution of the first populations of galaxies and clusters will provide extremely powerful tests of the validity and predictions of this hierarchical model.

During the next decade the simultaneous increase in the telescope collecting area of new facilities and their location at ground-based sites with the highest atmospheric transmission, and the availability of larger-format filled-array bolometer cameras promise to provide observational sub-mm data with greater sensitivity, resolution and unprecedented image-fidelity. The Large Millimetre Telescope (LMT) is one example of the next generation of mm and sub-mm telescopes that will lead the assault on the general question of *"how does structure form in the early universe and evolve to ultimately form the distribution of galaxies and clusters that define the* cosmic web *of filamentary structures and voids that are observed in the local universe?"*

The current status of the construction of the LMT, its anticipated performance and specifications are described in §2. As the epoch of LMT first-light and early science approaches, we summarise the ad-

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vantages that the LMT will exploit to detect the populations of high-redshift optically-obscured dusty starburst galaxies and AGN that produce the extragalactic background at sub-mm wavelengths, and the ability of the LMT and its suite of instrumentation to search for high-redshift clusters in the early universe ($z > 1$) via the Sunyaev-Zel'dovich effect.

2. THE LARGE MILLIMETRE TELESCOPE

The 50-m LMT, designed by MAN Technologie, is a bi-national collaboration between México and the U.S.A. The institutions leading this effort are the Instituto Nacional de Astrofísica, Optica y Electrónica (INAOE) and the University of Massachusetts (UMass) respectively. The selected telescope site of Volcán Sierra Negra (lat. ~ 19 deg), ~ 100km east of INAOE, is at an altitude of 4,640 m and provides excellent millimetre wavelength transmission with a median opacity $\tau_{225\,\mathrm{GHz}} < 0.12$ (1^{st} quartile < 0.07) between October and May. Occasional 850μm observations will also be possible during the best conditions ($\leq 10\%$) when $\tau_{340\,\mathrm{GHz}}$ is < 0.4. During the summer months Volcán Sierra Negra remains an excellent 3 mm site.

The LMT is an open-air telescope which has been designed to provide a pointing accuracy of ~ 1 arcsec under median wind-loading conditions (v < 4.5 m/s). A surface accuracy (r.m.s.) of 100μm for the primary aperture is anticipated during the initial period of operation, with an eventual goal of 70μm providing effective collecting areas of ~ 500, 750 & 1300 m^2 at 0.85, 1.1 & 3.3mm respectively. Consequently the LMT will be the largest and most sensitive single-aperture telescope operating at $\sim 0.85 - 4$ mm when scientific operation begins following *first-light* in the year 2008. The combination of the large-collecting area and available FOV (8 arcminutes in diameter) will provide the LMT with extremely fast-mapping speeds, an advantage that will be exploited by the first-light and future generations of facility and guest instruments (§2.2).

2.1. *Construction & Schedule*

The majority of the LMT structure, including the azimuth-track, bogies, alidade, ballast cantilevers, receiver cabins and control room, antenna back-structure and quadrupod (to support the 2.5 m carbon-fibre secondary mirror) is complete (Fig. 1). Within the LMT foundations the areas that will include a kitchen, dormitories, bathrooms are complete and the usual utilities (water,plumbing, electricity, air-conditioning) will be fully installed before the end of 2005. Other areas of the foundation will eventually be converted into receiver preparation rooms and workshops for scientific operation and maintenance. The upper-control room in the receiver-cabin, and the living-area in the foundation will be fed with supplemental oxygen. The antenna back-structure will be lifted onto the elevation axis in September 2005, and secondary-mirror support will be lifted into place shortly afterward. Following the installation of the azimuth and elevation drive motors, mechanical commissioning of the telescope will begin in early 2006.

The most significant area of LMT construction that remains to be completed is the fabrication and installation of the telescope surface which consists of 5 concentric rings of individual panel-sections. A single panel-section will be made from a number of smaller sub-panels (which are different in size for each ring of panels) which are fabricated as an electro-formed nickel skin with a rhodium reflecting-surface bonded to an aluminium honeycomb. The sub-panels are attached with adjusters (that correct the large-scale errors in the shape of any individual panel) to a carbon-fibre reaction-structure which is connected with actuators to a steel sub-frame. The entire panel-section is then inserted into the backing structure of the antenna. The controlled actuators allow each panel section to be moved in 3 orthogonal axes with respect to their neighbouring panels to preserve the desired shape of the entire primary surface under the influences of gravity and the normal temperature gradients within the telescope structure and antenna. The surface-panels for the inner ring are currently being fabricated.

2.2. *Instrumentation*

The suite of "first-light" instrumentation for the LMT is in an advanced state of preparation, and some instruments (SEQUOIA and AzTEC) have already been commissioned on other (smaller) mm and sub-mm telescopes. The basic properties of the instruments are summarised below, and more information regarding their anticipated performances can be found on the LMT web-pages (www.lmtgtm.org).

2.2.1. *Heterodyne systems*

- **SEQUOIA:** 32 beams - dual polarization, single side band (SSB) with 40K $<$ $\mathrm{T_{Rx}}$(SSB) $<$ 120K. RF bandwidth 85–115 GHz. IF bandwidth 5–20 GHz. No mechanical tuners.

- **1mm receiver:** single-beam, dual polarization. $\mathrm{T_{Rx}}$(SSB) $\leq$ 80K). RF bandwidth 210–275 GHz. IF bandwidth 4–12 GHz.

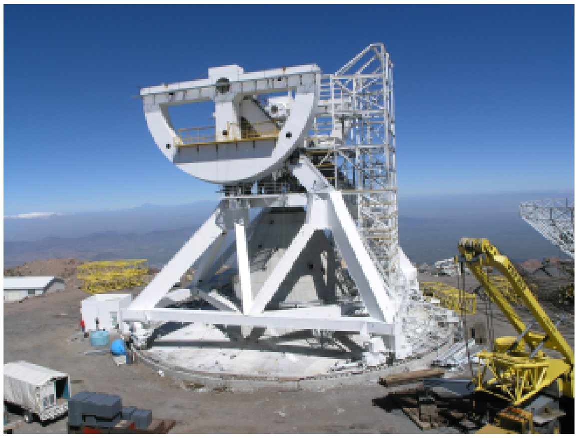
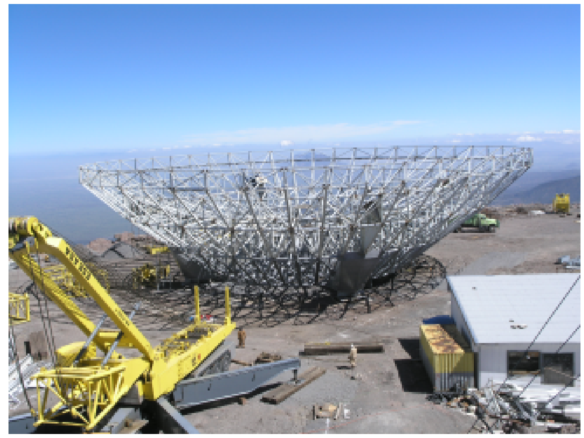

Fig. 1. **Left:** The LMT azimuth-track, bogies, alidade, ballast cantilevers and receiver cabin (open-frame structure) are nearing completion before the installation of the antenna. **Right:** Backing-structure of LMT antenna. In the foreground one of the two 1000-ton cranes required for the lift of the antenna onto the elevation mount (to take place in September 2005) is being prepared.

- **Redshift Search receiver:** 2 beam, dual-polarization (SSB) 40K < T_{Rx}(SSB) < 80K. RF bandwidth 75–110 GHz. IF bandwidth 5–40 GHz.

- **Auto-correlation spectrometer**

2.2.2. *Continuum systems*

- **AzTEC:** (formerly Bolocam II)**:** 144-pixel Si-Ni "spider-web" bolometer array, using NTD-Ge thermistors, operating at either 1.1mm or 2.1mm with a FOV of 2.4 sq. arcmins. NEFD $\sim$ 3 mJy Hz$^{-1/2}$ per pixel at 1.1mm (assuming $\tau_{225GHz} \sim 0.12$) and a mapping speed of 0.36 deg^{2}hr^{-1}mJy^{-2}.

- **SPEED:** prototype 4-pixel frequency-selective bolometer (FSB) array, using TES thermistors, operating simultaneously at 0.85, 1.1, 1.3 and 2.1mm with NEFDs of $3.3 - 0.9$ mJy Hz$^{-1/2}$ respectively. The 16 SPEED TES detectors are multiplexed and read out with SQUIDs. A larger-format 256-pixel camera (CIX) has been proposed.

Some examples of early-science programmes to be conducted on the LMT with AzTEC and SPEED (Wilson et al. 2004), which will shortly be commissioned on the 15-m JCMT[3] and the 10-m HHT respectively are highlighted below (§3).

The LMT Observatory is now planning *2nd-generation* instruments which generally include larger-format heterodyne and continuum arrays (e.g. One Millimeter Array - OMAR; Cluster Imaging Experiment - CIX) to utilize more efficiently the available FOV and increase the LMT performance.

[3]AzTEC was successfully commissioned on the JCMT in June 2005 and will return to the JCMT between October and December 2006 to conduct a full scientific programme.

3. DETECTING THE EPOCH OF FORMATION OF MASSIVE GALAXIES AND CLUSTERS

Measurements of the millimetre to X-ray wavelength extragalactic background show two broad spectral components (ignoring the 2.7 K black-body contribution from the CMB): one that peaks in the sub-mm to FIR regime at $\sim 200\mu$m, and the other that peaks in optical–IR regime at $\sim 1\mu$m. The integrated extragalactic background spectrum demonstrates that $\sim 50\%$ of the activity due to starformation and nuclear accretion from AGN throughout the history of the Universe has taken place in a heavily-obscured interstellar medium. Despite the comparable strengths of the optical–IR and FIR–submm backgrounds, < 1 sq. degree of the extragalactic sub-mm sky has been mapped with sufficient sensitivity and spatial resolution, resolving only a small fraction ($\leq 15\%$) of the FIR (200μm) background into a population of luminous high-z starburst galaxies.

Rest-frame FIR to mm wavelength observations provide a "transparent" view into the cores of star-forming molecular-clouds, and therefore these data have the ability to detect violent star formation in dusty and gas-rich galaxies which can be "missed" in searches at rest-frame optical–UV wavelengths. Furthermore, due to a strong negative k-correction, mm-wavelength LMT observations are able to trace the evolution of star formation in dusty galaxies throughout a large volume of the high-redshift universe (in principle with as much ease at $z \geq 10-20$ as

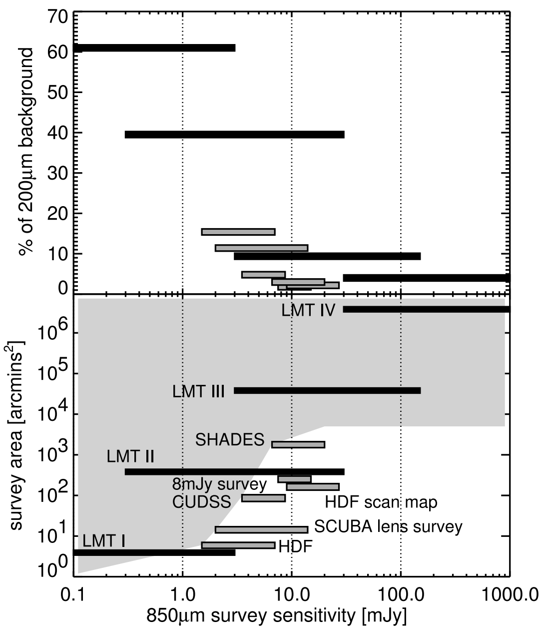

Fig. 2. A comparison of the 1.1 mm LMT surveys with AzTEC and existing 850μm JCMT surveys. **Lower panel:** the equivalent 850μm sensitivity to point sources and the survey-areas mapped by the JCMT (850μm) and LMT (1.1 mm) telescopes. The light-grey rectangles represent the range of depth and areas covered by existing SCUBA surveys. The potential LMT key-project surveys are shown as black rectangles. The ranges of flux densities probed by the individual AzTEC surveys reflect the interval between the confusion-limit (in the deepest surveys) or the lower 3σ sensitivity-limit of the survey, and the maximum flux density corresponding to the source surface-density N $>$ S_{max}, where only one source with flux S_{max} is expected to be detected in the survey area. The light-grey shaded area shows the unexplored region of the parameter-space prior to these LMT surveys. **Upper panel:** the fraction of the FIR (200μm) background resolved by the same LMT and JCMT surveys (with the same colour convention) as those shown in the lower-panel, demonstrating the greater capabilities of the LMT to probe the range of galaxy populations that contribute to the FIR background.

at $z \sim 1$ provided luminous starburst galaxies have already formed at such extreme redshifts). It is possible to test competing galaxy formation models with LMT surveys using the extragalactic source-counts, redshift distribution and the large-scale clustering information, to determine whether sub-mm galaxies represent the rapid formation of massive (elliptical) systems in a single violent collapse of the material in the highest-density peaks of the underlying large-scale matter distribution, or whether they are built over a longer period from the continuous merging of lower-mass systems with much more modest rates of star formation. Examples of simulated extragalactic LMT surveys and their analysis (including the clustering properties of the mm-wavelength galaxy population) have been presented by Hughes & Gaztañaga (2000) and Gaztañaga & Hughes (2001).

Due to the higher mapping-speed and increased sensitivity of the LMT and hence lower extragalactic confusion limits, it will be possible to resolve a significant fraction of the entire millimetre–FIR wavelength background into individual luminous starburst galaxies (with $L_{FIR} > 10^{11} L_{\odot}$). Fig.2 demonstrates that a series of 1.1 mm LMT surveys conducted with AzTEC will resolve $\sim 60\%$ of the FIR background and $\sim 100\%$ of the 1.1 mm background, providing a catalogue with $> 10^4 - 10^5$ sources to follow-up at X-ray to radio wavelengths in order to understand the physical nature and evolutionary history of the dusty high-z galaxies that dominate the emission of the mm–FIR extragalactic background.

Initial searches for larger-scale structures in the Universe (e.g. clusters) will also be undertaken with the LMT by making observations of the Sunyaev-Zel'dovich effect with the AzTEC camera, achieving a detection rate of ~ 1 cluster ($> 10^{14} M_{\odot}$) per hour in confusion-limited (due to dusty galaxies) surveys. By providing sufficient sensitivity and resolution at 2.1 mm, the LMT can simultaneously separate (spatially and spectrally) the extended CMB anisotropy due to the S-Z effect from massive clusters and the contaminating signal from the population of point-like dusty starburst galaxies at $z > 1$. Follow-up observations with SPEED will constrain the spectral shape and strength of the S-Z signature between 2.1–0.85 mm.

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