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DETERMINING THE HISTORY OF OBSCURED STAR FORMATION WITH THE GTC AND THE GTM

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RESUMEN

La finalización de la construcción y puesta a punto de GTC y GTM tienen calendarios similares. A partir de 2005 GTC y GTM van a comenzar las observaciones científicas, llevando a cabo estudios espectroscópicos y de imagen con sensibilidad sin precedentes en el IR cercano y medio y en longitudes de onda milimétricas. Los mapas submilimétricos con SCUBA han descubierto una importante población de galaxias starburst luminosas. El GTM, con su capacidad de cartografiado 100 veces más rápida que la de SCUBA, obtendrá mapas milimétricos más extensos, con mayor capacidad y resolución más alta. La distribución en corrimientos al rojo de esta población altamente evolucionada (que los corrimientos al rojo del lejano IR y radio sitúan su máximo en $z = 3$), la historia de su formación estelar y la fracción de AGN permanecen aún escasamente conocidos. En esta contribución resumimos un posible Proyecto Clave que combina mapa coordinados y en colaboración entre GTC y GTM. Describimos las observaciones de seguimiento de las galaxias seleccionadas milimétricamente que hacen uso de las capacidades únicas en imagen y espectroscopía multiobjeto de EMIR y la sensibilidad en el IR medio de CanariCam.

ABSTRACT

The completion of the construction and commissioning of the Gran Telescopio Canarias (GTC) and the *Gran Telescopio Milimétrico* (GTM) have similar schedules. From 2005 onwards, the GTC and the GTM will begin scientific observations, conducting spectroscopic and imaging studies with unprecedented sensitivity at IR, mid-IR and mm wavelengths. Sub-mm surveys with SCUBA have discovered an important population of luminous starburst galaxies. The GTM, with a mapping speed 100 × faster than SCUBA, will provide more extensive mm-wavelength surveys with greater sensitivity and higher resolution. The redshift distribution of this strongly evolving population of sub-mm sources (which FIR–radio photometric redshifts suggest peaks at $z \simeq 3$), their star formation history, and AGN fraction all remain poorly constrained. In this paper we summarize a possible "Key Project" that combines coordinated and collaborative surveys on the GTC and GTM. Follow-up observations of mm-selected galaxies that utilize the unique IR imaging and multiobject spectroscopic capabilities of EMIR, and the mid-IR sensitivity of CanariCam are described.

Key Words: **COSMOLOGY**

1. INTRODUCTION

One of the major goals of observational cosmology is to acquire empirical data of sufficient diagnostic power to constrain and develop the numerous theoretical models for the high redshift Universe, ultimately leading to an understanding of the processes by which galaxies and clusters form and evolve from the initial underlying large scale matter fluctuations.

The field of observational cosmology will be revolutionized during the course of the next decade. This is because of the combination of sensitive imaging and spectroscopic surveys that are being conducted, or are shortly to begin, on the new generation of large optical and IR telescopes (e.g., Subaru, VLT, Hobby–Eberly, and the Gemini telescopes). These will be supported by UKIDSS, a series of wider area IR imaging surveys from UKIRT using WFCAM in 2004, and with VISTA from 2006 onwards. Within the next 4 years we can also expect the first imaging and spectroscopic surveys from the South African Large Telescope (SALT) and the Gran Telescopio Canarias (GTC). In the more distant future we can look forward to 30 m to 100 m telescopes with optical and IR capabilities which are currently under design.[3] This greatly enhanced capability in the optical–IR over the next decade will be supported by an equally powerful variety of new ground-based, airborne and satellite telescopes operating at mid-IR to mm wavelengths. In their approximate order of completion and commissioning we have GBT, SMA,

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SIRTF, BLAST, SOFIA, GTM (or LMT), *ASTRO-F*, *Herschel*, and ALMA.

Here, we summarize a selection of the cosmological projects that can be carried out through coordinated observing programmes with the GTC and the Gran Telescopio Milimétrico (GTM), or Large Millimetre Telescope (LMT). The GTC has been described elsewhere in these proceedings. The GTM, however, requires a brief introduction. The GTM is a joint bi-national collaboration between INAOE and the University of Massachusetts at Amherst, USA. The GTM has a 50 m primary aperture, consisting of 180 panels, and is the largest single-dish telescope optimized for millimeter wavelength observations (1–4 mm). The telescope is currently under construction on Sierra Negra (4600 m), in the Mexican state of Puebla at a northern latitude of 19 degrees, approximately 115 km and a 2 hour drive from INAOE. The GTM performance relies strongly on maintaining the open-loop "active" surface with a total surface accuracy of $\leq 70\ \mu$m under all anticipated gravitational and thermal loads.

The instrumentation development programme for the GTM will provide a suite of state-of-the-art coherent and incoherent detection receivers for first light, expected in 2004. In particular, the GTM will have two instruments that will supply the majority of the data at cosmologically important redshifts described in this paper: BOLOCAM-II, a 144 pixel focal plane continuum array; RESMA (REd-Shift MAchine), a broad band 3 mm spectrometer using MMIC amplifiers that will offer an instantaneous bandwidth of ∼30 GHz. More detailed information on the telescope and instrumentation is available at http://www.lmtgtm.org.

2. THE CASE FOR MILLIMETER WAVELENGTH SURVEYS

There is compelling observational evidence that much of the ongoing star formation in the young Universe is *hidden* from optical/UV surveys. For example, using a Lyman break color selection technique (Steidel et al. 1996), more than 3000 high z galaxies have been identified in ground-based and *Hubble Space Telescope* (*HST*) faint galaxy samples, with > 800 galaxies already spectroscopically confirmed at $z \simeq 2$ with star formation rates (SFRs) $\sim$1–5 $h^{-2}\ M_{\odot}\ \mathrm{yr}^{-1}$. However the attenuating effects of dust, inevitably associated with star formation, mean that SFRs estimated from these rest-frame UV luminosities must be treated as strict lower limits. Near-IR observations of rest-frame Balmer line emission suggested an upward correction factor to the SFRs of 2–15× (Pettini et al. 1998). Alternative, and arguably more robust, measurements derived from rest-frame FIR luminosities imply SFRs 600 times greater than that estimated from the UV luminosity (Hughes et al. 1998; Cimatti et al. 1998).

Therefore, any probe of star formation which is insensitive to the obscuring effects of dust will have a tremendous advantage. Such a transparent view of the high z Universe is provided by sub-mm and mm observations, which now have the instrumental sensitivity (e.g., SCUBA, MAMBO) to detect the formation of young, massive galaxies heavily enshrouded in dust. The absorption and re-radiation by dust of the UV emission means that at early epochs galaxies are expected to be extremely bright in the rest-frame FIR, and therefore at high redshift, also bright at sub-mm wavelengths. The unique strong negative k-correction (e.g., Blain & Longair 1993) that makes cosmological surveys feasible at sub-mm and mm wavelengths also allows the surveys to sample large volumes of the high redshift Universe.

Consequently, the rest-frame FIR luminosity of galaxies is expected to show a significant amount of evolution, particularly in the case of massive elliptical galaxies, which, at the present epoch, radiate only a few percent of their bolometric luminosity at FIR wavelengths. Sub-mm observations which measure the rest-frame FIR spectral energy distributions (SEDs), luminosities, and SFRs of high z galaxies therefore provide a powerful method of quantifying the star formation history of massive galaxies in particular, and of the high z Universe in general.

3. SURVEYING THE EXTRAGALACTIC SKY WITH THE GTM

One of the primary science goals for the GTM is to first identify and then characterize the population of galaxies that dominate the contribution to the extragalactic sub-mm–mm background emission. The main advantage of the GTM and its instrumentation is the greatly enhanced mapping speed compared to the current facilities (e.g., ∼100 times faster than SCUBA on the JCMT and MAMBO on the IRAM 30 m), and with a beam size of ∼6 arcsec at 1.1 mm, the GTM has a spatial resolution comparable to, or higher than, any other single-dish telescope at mm or sub-mm wavelengths.

The star formation history of the high z starburst galaxy population can be determined from an accurate measurement of the integral mm source counts, and the luminosity and redshift distributions of mm-selected galaxies. By conducting a series of cosmological mm surveys with the GTM that cover

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a sufficiently wide range of complementary depths and areas, complemented by BLAST observations at shorter sub-mm wavelengths (Devlin et al. 2001), it is possible to discriminate between competing models of massive galaxy formation. Furthermore, the evolution of the luminosity function and clustering of sources in these surveys will reveal whether high z mm galaxies are the progenitors of present-day massive elliptical galaxies, and whether these galaxies form via the classical picture of early monolithic collapse at high redshifts, or via continuous merging of haloes over a wide range of redshifts (Kauffmann, White, & Guiderdoni 1993).

4. FOLLOW-UP OBSERVATIONS OF GTM SURVEYS WITH THE GTC

The GTM and the GTC can expect to play an important combined role in addressing some of the outstanding problems from the first series of sub-mm surveys. The existing 850 μm SCUBA and 1.25 mm MAMBO surveys have been limited to areas of 0.001–0.2 deg^2 (e.g., Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Eales et al. 1999; Scott et al. 2002; Borys et al. 2002; Bertoldi et al. 2001) and are restricted in their ability to constrain evolutionary models of the sub-mm galaxy population.

The practical reasons for these limitations have been described elsewhere (Hughes 2000) and can be summarized as follows: restricted wavelength coverage (enforced by the limited number of FIR–mm atmospheric windows available to ground-based observatories); low spatial resolution (resulting in both a high extragalactic confusion limit and poor positional accuracy); restricted field of view with the current sub-mm and mm bolometer arrays (typically 5 sq. arcmin); and low system sensitivity (a combination of instrument noise, size of telescope aperture, and telescope surface accuracy, sky transmission, and sky noise) which restrict even the widest and shallowest sub-mm surveys to areas < 0.2 deg^2. In the effort to obtain these wide area shallow surveys, the current SCUBA and MAMBO observations are necessarily only sensitive to the most luminous star forming galaxies ($L_{\rm FIR} > 10^{12} L_\odot$, or SFR $> 100\ M_\odot$ yr^{-1}), assuming the population is dominated by galaxies at redshifts > 1.

Although the dynamic range and wavelength coverage of existing sub-mm source counts will be significantly increased during the next five years (from surveys with GTM, BLAST, *SIRTF*, and *ASTRO-F*), there will remain the need for sensitive optical, IR, and mid-IR follow-up imaging and spectroscopy of the detected starburst galaxies and AGN, in particular those identified in the GTM surveys. To understand better the physical nature and evolutionary history of the mm sources we must identify their observed IR counterparts, measure their redshift distribution, characterize their rest-frame optical morphological appearance, determine the ages and metallicities of their stellar populations, and quantify the AGN and starburst fraction present in this unbiased mm-selected sample of high z galaxies.

We briefly describe below some of the key follow-up observations of GTM surveys that can be made with the IR (EMIR) and mid-IR (CanariCam) instrumentation on the GTC.

4.1. *The counterparts and redshift distribution of mm-selected sources*

The current 850 μm SCUBA and 1.25 mm MAMBO surveys (with 15 and 11 arcsec FWHM resolution respectively) are struggling to identify the optical counterparts of the sub-mm-detected sources. In part, this is due to the large sub-mm beam sizes, and the positional errors of $\sim$2–3 arcsec that are associated with the low S/N ($< 5\sigma$) detections of sub-mm sources.

Although the positional errors can be improved to levels of sub-arcsec accuracy with follow-up radio (VLA) and mm–interferometric (IRAM PdB) observations (Frayer et al. 1998; Gear et al. 2000; Lutz et al. 2001), ambiguous optical identifications still remain (e.g., Smail et al. 1999; Downes et al. 1999). It should be no surprise that sub-mm-selected galaxies, including those with mm–interferometric detections, do not always have optical counterparts, since high z galaxies observed in the earliest stages of formation may be heavily obscured by dust. Indeed, this is the most compelling reason for conducting the sub-mm surveys in the first instance. Searches for counterparts at longer IR wavelengths have proven to be more successful (Smail et al. 1999; Frayer et al. 2000; Gear et al. 2000; Lutz et al. 2001; Dunlop et al. 2002) and have shown earlier identifications of lower z bright optical galaxies to be the incorrect counterpart to the sub-mm galaxies. The natural consequence of these ambiguous and potential misidentifications is an inaccurate determination of redshift distribution, luminosities and star formation history of high z galaxies.

4.2. *IR imaging and multiobject spectroscopy with EMIR*

One of the key follow-up observations to made of mm-sources identified in the GTM surveys are deep IR (K band) observations. The UKIRT and Subaru

K band imaging of SCUBA sources indicates that IR imaging must reach $K > 21$ and in some cases be as deep as $K \sim 23.5$ before the IR counterpart to the sub-mm sources can be detected. In the case of mm surveys of lensing clusters, the amplification of the IR emission from the background mm galaxies will allow the detection requirement to be relaxed to $K > 20$.

At the present time the number of detected IR counterparts to sub-mm sources is too small to allow an accurate prediction of the feasibility of the IR observations with EMIR. We will assume conservatively that a limit of $K = 23.5$ (5σ) must be reached. This requires ∼4 hours of integration time with the GTC and EMIR over a field of 36 sq. arcmin.

A possible intermediate-sized GTM key project is a 1 sq. deg 1.1 mm survey with the array camera BOLOCAM-II, to the same equivalent depth as the 850 μm SCUBA survey of the Hubble Deep Field (Hughes et al. 1998). This GTM survey will take approximately 200 hours (or about 40 nights) to complete. At a detection threshold of 5σ (1 mJy) we expect to detect ∼1000–3000 sources/sq. deg in the GTM survey. At brighter flux densities, S(1.1 mm) $\simeq$ 3 mJy, comparable to the sub-mm sources detected in the widest area SCUBA surveys, the surface density will still be > 100 sources/sq. deg Therefore, given the field of view of EMIR (36 sq. arcmin), it does not make sense to follow up individual mm sources. It is far more efficient to uniformly map the entire 1 sq. deg field in the IR with EMIR, taking only 400 hours, which, with a suitable choice of survey field, could be completed in about 60 nights on the GTC (within a factor of two of the time taken on the GTM). This modest follow-up survey of the GTM sources, requires only 15 nights per semester on the GTC (assuming 7–10 usable hours per night), for four consecutive semesters, and at the same time generates, as an equally valuable by-product, a deep 1 sq. deg K band extragalactic survey. If the 5σ detection limit is reduced to $K = 23.0$, this survey can be completed in only 160 hours (or about 4 weeks). A useful comparison can be made with the planned UK Infrared Deep Sky Surveys (UKIDSS), a series of IR public surveys that will be made with the Wide Field Infrared Camera (WFCAM) using 1000 nights of UKIRT telescope time over 7 years, starting in 2004. The ultra-deep IR extragalactic survey, as part of UKIDSS, will also reach $K = 23.0$ over 0.77 sq. deg and requires 271 hours. Thus the equivalent EMIR survey on the GTC can be completed in less than 50% of the time for the UKIDDS ultra-deep survey.

It is likely that such an IR survey is already planned as part of a key project for EMIR. This is one example, therefore, given suitable coordination, of a collaborative proposal between the GTC and the GTM that provides the required dataset for both facilities in the most efficient manner.

The surface density and expected redshift distribution of mm sources, and sensitivity requirements are ideally suited to an IR multiobject spectrograph on a 10 m class telescope. One of the unique capabilities of EMIR and the GTC is the ability to conduct multiobject IR spectroscopy of 45 sources over a field of 24–36 sq. arcmin. The accurate determination of the redshift distribution for the population of mm-selected sources is one of the key combined science goals of the GTM and GTC. The current estimates, based on photometric redshifts, suggests that the majority of the galaxies detected by the GTM will be in the redshift range $z = 2$–4, with the possibility that some large fraction < 50% could be at higher redshifts, $z > 4$ (Aretxaga et al. 2002). EMIR can determine the spectroscopic redshifts of mm-selected galaxies using rest-frame optical emission lines at $\lambda <$ 2000–8000 Å. With the mm source counts of 1000–3000 sq. deg in the GTM survey proposed above, there will be a maximum of 20–30 targets per field. These can be accommodated by the 45 available slitlets on EMIR, which allows the opportunity to measure the redshifts of a similar number (15–25) of optically bright galaxies in the field. These data, which require a similar maximum integration time of 4 hours per field, can determine the clustering properties of both optically selected and mm-selected populations, and the correlation between them. A measure of a few hundred (∼400) spectroscopic redshifts (requiring < 80 hours) would be sufficient to significantly advance our understanding of the evolutionary history of the mm galaxies detected by the GTM. For comparison, the detection of Hα in a K band CGS-4 spectrum from UKIRT of the lensed SCUBA source SMM14011+0252 (at $z = 2.565$) required 9 hours of integration (Ivison et al. 2000). These IR spectrosopic data (providing emission and absorption line information) will be complemented by mm-wavelength spectroscopy on the GTM using RESMA, the "redshift machine". The large instantaneous bandwidth ($\Delta\nu \sim 30$ GHz) of RESMA at 90 GHz will allow sensitive searches for molecular CO lines from mm galaxies over the entire wide range of all reasonable redshifts ($z \sim$ 0–8). The CO spectra at mm wavelengths will confirm not only the IR redshifts, and therefore the identifications of the IR counterparts, but also will provide

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estimates of the gas mass and excitation conditions of the molecular phase of the ISM in these high z galaxies.

4.3. *Mid-IR imaging of mm-selected galaxies with CanariCam*

The AGN fraction in the sub-mm SCUBA population of galaxies, based on follow-up hard X-ray observations, has been estimated as $\leq 10\%$. However, the possibility that Compton-thick tori hide a larger fraction of more deeply embedded AGN cannot be ruled out. The mid-IR is another spectral regime which is sensitive to the presence of an AGN, revealed by an enhanced thermal luminosity at 5–60 μm because of the heating of dust grains to a higher temperature by this additional accretion-driven source of energy. Typical examples of heavily obscured (buried) AGN at high and low z exist (e.g., Mrk 231, IRAS10214+4624). The increased fraction of mid-IR/FIR luminosity in starburst galaxies is a strong indication that an AGN (possibly hidden) is also present.

Assuming the population of mm-selected GTM galaxies to be distributed between $z = 2$–4, then the mid-IR imaging camera, CanariCam, on the GTC has the possibility of detecting the rest-frame 5 μm emission. These observations are still at the limit of feasibility and require that CanariCam is equipped with a broad Q band 20 μm filter, that the emissivity of the telescope is sufficiently low, and that the atmosphere has the necessary transparency. Furthermore, the observed 20 μm fluxes (rest-frame 4–7 μm) of the GTM starburst population at $z = 2$–4 are expected to be in the range of 50–200 μJy. Assuming a 5σ 20 μm sensitivity of $\sim$200 μJy (scaled from the CanariCam 10 μm sensitivity using the relative N and Q band sensitivities for Michelle on UKIRT) in 4 hours, it is clear that a significant investment of telescope time (4–50 hours) will be required for each individual target. A flux-limited CanariCam survey a restricted number of GTM sources brighter than 200 μJy at 20 μm (observed wavelength), however, may still offer an indication of whether the hard X-ray surveys have underestimated the AGN fraction in the most luminous high z mm-selected galaxies.

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