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RESOLVING THE FIR–SUBMILLIMETRE EXTRAGALACTIC BACKGROUND FROM DOME C, ANTARCTICA

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Abstract. Recent advances in bolometric detector technology have allowed submillimetre (submm) wavelength measurements to contribute important data to some of the most challenging questions in observational cosmology. The availability of large-format filled-array cameras during the next decade, however, promises to provide far-infrared (FIR) to millimetre (mm) observations with unprecedented imaging fidelity. The simultaneous increase in the telescope collecting area of new facilities, and their location at ground-based sites with the highest atmospheric transmission will provide observational data with greater sensitivity and resolution. With the opening of the Italian/French Concordia station at Dome C in Antarctica there is now an exciting opportunity to make unique FIR–submm wavelength observations ($200 - 850\mu$m) through atmospheric windows that are *almost open to space*. The development of submm astronomy from Dome C, undertaken with a phased-programme of increasingly larger telescopes, will make critical observations of the high-redshift universe. In particular, we argue that a long-term strategy for Dome C should include plans to construct a 30-m telescope with a large field-of-view (≥ 0.1 sq. deg), designed and optimized to operate at $\sim 200\mu$m. With such a single-dish facility it will be possible to resolve 100% of the population of galaxies that contribute to the integrated FIR-submm extragalactic background. In this paper we describe how a large-aperture submm telescope at Dome C will provide unique data to address fundamental questions and *killer science* regarding the evolutionary history, nature and large-scale distribution of the population of high-redshift optically-obscured starburst galaxies.

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1 Introduction

Observational evidence suggests that much of the on-going star formation in the universe takes in a heavily-obscured interstellar medium. 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, submm and mm wavelength 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 $z \geq 8$ as at $z \sim 1$). Given this, it is then possible to test 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. Eventually, sensitive and high-resolution interferometric imaging surveys with instruments like ALMA will provide a more dramatic and precise description of the manner in which massive galaxies form (i.e. single or multiple sources associated with the sub-mm emission?). In the meantime, however, the source-counts, redshift distribution and the large-scale clustering information obtained from the current generation of submm surveys are providing useful, albeit crude, initial tests of competing galaxy formation models (e.g. van Kampen et al. 2003).

With the opening in Antarctica of the Italian/French Concordia station at Dome C (lat. -75^o, long. 123^oE), for year-round observations expected in the near future, and the early indications that this high-altitude site (at 3280 m) has the best atmospheric transparency and stability at short submm wavelengths of any ground-based observatory in the world, it is now appropriate to consider how FIR–submm extragalactic surveys from Dome C can contribute to our understanding of the earliest stages of structure formation and its subsequent evolution into the clusters and galaxies observed at high-redshift.

More specifically, before the full evolutionary history of the galaxy populations that dominate the integrated FIR–mm extragalactic background emission can be understood, we must (i) identify the individual galaxies that supply the FIR-mm background emission (which contributes $\sim 50\%$ of the overall energy budget of the universe), and determine their redshifts; (ii) measure their individual bolometric rest-frame FIR luminosities, star formation rates and the evolution of their integrated luminosity functions; (iii) determine the fraction of AGN in the various FIR–mm galaxy populations; (iv) measure the spatial clustering properties of these FIR–mm galaxies; (v) characterize the multi-wavelength spectroscopic and continuum properties of these dusty FIR–mm galaxy populations.

In this brief paper we consider the most outstanding of the above questions (or "*killer science*") and summarise the opportunity for a large single-dish submm telescope at Dome C to resolve for the first time the extragalactic FIR-submm background at 200-450μm. The practical advantages of submm astronomy from

Dome C are also discussed. For the purpose of clarity we define 200μm to represent the FIR wavelength regime, and 350–850μm defines the sub-mm regime.

2 The potential for submm astronomy from Concordia Station, Dome C

The results from the UV–IR site testing of the atmospheric conditions above Dome C are described in detail elsewhere in these proceedings. In general, the benign and stable environment of Dome C appears ideal for submm astronomy with low median wind-speeds (~ 3 ms^{-1}) and the extremely low-levels of precipitable water vapour (≤ 0.25 mm) that have been measured during the austral summer. The site-testing also indicates that the excellent transmission persists over weeks-long continuous periods. It is anticipated that the first site-testing during the austral winter, to be conducted in 2005, will indicate even dryer (0.15 mm PWV) and more stable atmospheric conditions, and also that direct observations of the submm transparency will demonstrate that Dome C has "open windows" (with $\sim 40\%$ transmission) at 200, 230 and 290μm. If the 2005 austral winter-season of site-testing is successful, then the long-term stability and unprecedented high atmospheric transmission will justify the claim that Dome C is the "best" ground-based site for submm astronomy, surpassing the recognised qualities of Manua Kea (Hawaii), the Atacama Desert (Chile) and the South Pole.

In addition to the exceptional atmospheric conditions, there are other unique practical environmental reasons that will benefit submillimetre astronomy from Dome C. For example, the temperature (200-220 K) and long-duration of the days and nights in Antarctica (during the austral summer and winter respectively) means that there will there be a low emissivity and greater diurnal and nocturnal temperature stability of the telescope surface and structure, compared to observatories at equatorial latitudes. Astronomical sources also traverse the sky with more constant elevation. The advantageous result of these factors, i.e. (i) atmospheric stability (wind-speed, sky-transmission, sky-noise and sub-mm seeing), and (ii) the minimal elevation-dependent gain and thermal stability of the telescope, is that they enhance the ability of a large-aperture (~ 30 m) submm telescope operating at $\sim 200 - 850\mu$m to achieve high pointing-accuracy and high-precision astronomical calibration.

3 Resolving the FIR–submm extragalactic background at 200–300μm

The first generations of cosmological surveys at submm and mm wavelengths have been conducted primarily with the SCUBA (Holland et al. 1999) and MAMBO cameras, which both use modest-sized bolometer arrays (~ 100 pixels), on the 15-m JCMT and 30-m IRAM telescopes respectively. The measured source-counts from these combined extragalactic surveys at 850μm and 1.1 mm respectively, however, are only calculated over a small dynamic-range in flux density ($\sim 0.2 - 15$ mJy at 850μm) from survey-areas ranging from 0.002 – 0.5 deg^2 (Smail et al. 1997; Hughes et al. 1998; Scott et al. 2002; Borys et al. 2003; Webb et al. 2003;

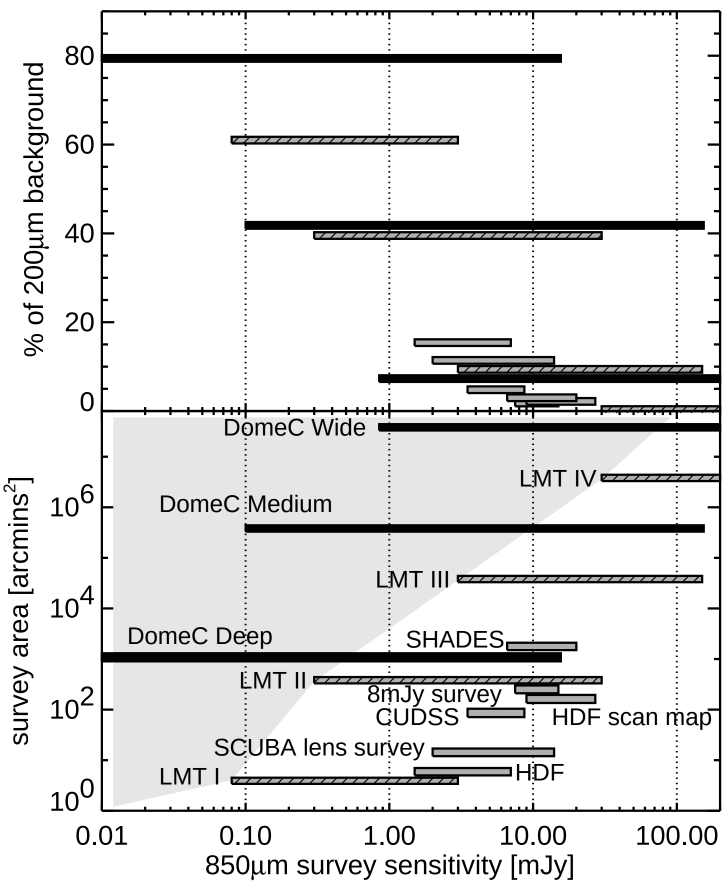

Fig. 1. The fraction of the 200μm extragalactic background resolved by representative mm (LMT), submm (JCMT) and FIR (Dome C) ground-based surveys with current and future instrumentation. *Lower panel:* The equivalent 850μm sensitivity to point sources reached in the various surveys, and the survey-areas mapped by the JCMT (850μm), LMT (1.1 mm) and Dome C (200μm) telescopes. The light-grey rectangles represent the range of depth and areas covered by various SCUBA surveys (see §3 for details and references). The potential LMT key-project surveys are shown as striped rectangles, and the future Dome C surveys (Deep - 1000 sq. arcmin; Medium - 100 sq. deg; Wide - 10000 sq. deg) are shown as solid black rectangles. The ranges of flux densities probed by the individual surveys reflect the interval between the confusion-limit (in the deepest surveys) or the 3σ lower-limit to the sensitivity of the survey, and the maximum flux density corresponds 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 the construction of a FIR telescope at Dome C. *Upper panel:* The fraction of the 200μm background resolved by the identical surveys (colour-scheme the same as the lower-panel) demonstrating the uniqueness of a large FIR–submm telescope at Dome C.

Greve et al. 2004). The practical reasons for the above limitations can be summarised as follows: restricted wavelength coverage (enforced by the few FIR–mm atmospheric windows available to ground-based observatories); low spatial resolution ($\sim 7-15''$, 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 $5\,\mathrm{arcmin}^2$); 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 with existing instruments to areas < 0.2 deg^2. Hence, in the effort to obtain these blank-field surveys, the current sub-mm observations are necessarily only sensitive to the most luminous and massive star-forming galaxies ($L_{\rm FIR} \sim 3 > 10^{12} L_\odot$, or SFR $> 300 M_\odot \mathrm{yr}^{-1}$), assuming that the population lies at $z > 1$.

Thus, despite 8 years of intense effort to map the submm sky with ground-based telescopes, it is only in the deepest SCUBA surveys ($\sigma_{850\mu\mathrm{m}} \sim 0.5\,\mathrm{mJy}$) that a significant fraction (30–100%) of the 850μm background has been resolved into discrete galaxies, yet these same surveys have only observed ≤ 70 sq. arcmin in total. Furthermore, an extrapolation of the SCUBA and MAMBO source-counts to shorter submm wavelengths indicates that the same populations of 850μm and 1.1 mm galaxies detected in these deepest surveys contribute less than 15% of the FIR background emission which peaks at $\sim 250\mu$m (see Fig. 1). The shallower ($\sigma_{850\mu\mathrm{m}} \sim 2.5\,\mathrm{mJy}$) and wider-area ($>300$ sq. arcmin) submm surveys provide only a few percent of the FIR background, whilst the anticipated heavily confusion-limited 1.1 mm surveys ($\sigma_{1.1\mathrm{mm}} \sim 0.01\,\mathrm{mJy}$) with the 50-m Large Millimetre Telescope will only increase the resolved fraction of the FIR background to $\leq 40-60\%$, despite detecting galaxies with more modest FIR luminosities ($L_{\rm FIR} \geq 10^{11} L_\odot$) and SFRs ($\geq 10-50 M_\odot \mathrm{yr}^{-1}$) out to extreme redshifts (potentially $z > 10$).

Although the above predictions are uncertain by a factor of 2 (due to the extrapolation of sub-mm and mm source-counts according to some evolutionary model based on < 100 galaxies with $> 4\sigma$ detections, the impact of clustering on the observed counts in the small-area surveys, and the lack of accurate information on the FIR–mm spectral energy distributions of this population), there is clearly a compelling and *killer science* case to design an instrument with the necessary angular resolution, sensitivity and mapping-speed to survey the extragalactic sky at $\sim 200-300\mu$m to a confusion level that is deep enough to resolve 100% of the FIR background. This proposed survey will reveal the population of dusty submm galaxies that have been "missed" due to either their lower-luminosity, colder ISM, lower redshift distribution or a combination of these factors. In contrast the lower spatial resolution of FIR-submm telescopes on sub-orbital payloads and satellites over the next decade (e.g. Spitzer, BLAST, ASTRO-F and Herschel) will not resolve a significant fraction of the FIR background, and whilst ALMA has the necessary resolution and may be able to operate for short periods of time in the 200μm atmospheric windows, ALMA lacks the wide-field mapping capability to survey the distribution of the galaxies that contribute the FIR background over large-areas (≥ 1 sq. deg).

4 A 30-m FIR-submm single-dish telescope at Concordia, Dome C

We assume that there will be a successful development of submm astronomy at the Concordia station over the next decade, with the installation and operation of a $\sim$ 2-m submm telescope to demonstrate the feasibility of the site, followed by a "pathfinder" 10-m class telescope (e.g. the Antarctic Submillimetre Observatory described by Luca Olmi, these proceedings). We suggest that the long-term plan for Concordia should also include an ambitious goal to build a 30-m single-dish sub-mm telescope at Dome C, with a key scientific goal – to resolve the FIR extragalactic background. We also take for granted that, on a timescale of $\sim$ 15 years, the technological and engineering challenges to build a large telescope that can operate in the environment of Dome C can be overcome. Moreover, the final telescope design must provide a significant field-of-view (≥ 0.1 sq. deg), and the focal-plane should be filled with fully-sampled arrays operating at 850, 450, 350 and 230μm (requiring "mega-pixel" cameras) with NEFDs of 40, 25, 15 and 8 mJy/Hz$^{1/2}$ respectively. An extrapolation of an evolutionary model fitted to the 850μm counts predicts that a 30-m sub-mm telescope operating at $\sim$ 230μm, with a beam size $<$ 2 arcsecs, will achieve a confusion-limit of $\sim$0.1 mJy. Figure 1 indicates that such a confusion-limited survey from Dome C will resolve $\sim 80-100\%$ of the FIR background. It is also essential, however, to measure the spatial distribution or clustering of this population, or equivalently to map an area large-enough ($\gg$ 1 sq. deg.) to negate the effect of cosmic-variance in the measured source-counts. Given that it would require $\sim$ 250 hrs to map 1000 sq. arcmin to a sensitivity of $3\sigma \sim 0.3$ mJy with a 30-m telescope at Dome C, it is clearly possible to consider mapping 1 sq. deg to the same depth since the 1000 hr survey at 200μm can take advantage of the continuous visibility towards some of the potential extragalactic survey fields and the stable atmospheric conditions. There is no telescope currently funded that could undertake such a survey. We also consider other key 200μm surveys from Dome C that cover interesting regions of the parameter space, including a shallow ($1\sigma \sim 20$ mJy) 10^5 sq. deg. survey to search for the rarest and most luminous star forming galaxies in the Universe, as well as providing valuable high-resolution FIR–submm data over a large-fraction of the available extragalactic sky to complement the next generations of IR–FIR–submm satellite experiments.

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