A SUBMILLIMETRE SURVEY OF THE HUBBLE DEEP FIELD: UNVEILING DUST-ENSHROUDED STAR FORMATION IN THE EARLY UNIVERSE

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Abstract

The advent of sensitive sub-mm array cameras now allows a proper census of dust-enshrouded massive star-formation in very distant galaxies, previously hidden activity to which even the deepest optical images are insensitive. We present the deepest sub-mm survey, taken with the SCUBA camera on the James Clerk Maxwell Telescope (JCMT) and centred on the Hubble Deep Field (HDF). The high source density on this image implies that the survey is confusion-limited below a flux density of 2 mJy. However within the central 80 arcsec radius independent analyses yield 5 reproducible sources with $S_{850\mu m} > 2$ mJy which simulations indicate can be ascribed to individual galaxies. These data lead to integral source counts which are completely inconsistent with a no evolution model, whilst the combined brightness of the 5 most secure sources in our map is sufficient to account for 30–50% of the previously unresolved sub-mm background, and statistically the entire background is resolved at about the 0.3 mJy level. Four of the five brightest sources appear to be associated with galaxies which lie in the redshift range $2 \leq z < 4$. With the caveat that this is a small sample of sources detected in a small survey area, these submm data imply a star-formation density over this redshift range that is at least five times higher than that inferred from the rest-frame ultraviolet output of HDF galaxies.

1 Star-Formation at High Redshift

The global star-formation history of the Universe [1], [2], [3], derived from optical-UV data, imply that the star-formation and metal-production rates were $\sim 10$ times greater at $z \simeq 1$ than in the local Universe [4], that they peaked at $z \simeq 1 - 1.5$ and that they declined to values comparable to those observed at the present day at $z \simeq 4$. However these optical-UV data may offer a distorted view of the evolution of the early Universe because the star-formation rate (SFR) in high-redshift objects is inevitably under-estimated unless some correction for dust obscuration is included in deriving the rest-frame UV luminosity [5]. Second, it is possible that an entire population of heavily dust-enshrouded high-redshift objects, as expected in some models of elliptical galaxy formation [6], have gone undetected in the optical/UV surveys.

At high redshifts ($z > 1$), the strongly-peaked far-infrared (FIR) radiation emitted by star-formation regions in distant galaxies is redshifted into the sub-mm waveband, and the resulting

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†Consortium membership as in [12]
large negative K-correction at submm wavelengths is sufficient to offset the dimming of galaxies due to their cosmological distances. Consequently the flux density of a galaxy at $\lambda \approx 850 \mu m$ with fixed intrinsic FIR luminosity is expected to be roughly constant at all redshifts in the range $1 \leq z \leq 10$.

Using the new sub-mm array camera SCUBA on the 15-m JCMT it is now possible to conduct unbiased sub-mm selected surveys and quantify the amount of star-formation activity in the young Universe by observing directly the rest-frame FIR emission from dust in high-redshift galaxies. In this paper we briefly summarise the first results from the deepest sub-mm SCUBA survey, complete to a flux density limit $S_{850 \mu m} > 2$ mJy, centred on the HDF. In contrast to mid-IR studies, such an $850 \mu m$ survey is predicted to be completely dominated by sources at $z \geq 1$, and the number of detectable sources is very sensitive to the high-redshift evolution of the dusty starburst population. A full description of these data, observing methods, reduction techniques, detailed analysis and interpretation is described elsewhere.

2 A deep sub-mm survey of the Hubble Deep Field

The 850$\mu m$ SCUBA survey of the HDF, with 14.7 arcsecs resolution, reaches a $1\sigma$ noise level of 0.45 mJy/beam and represents the deepest sub-mm map ever taken. The positions of the brightest (and most secure) 5 sources are given in table 1, together with their 850-$\mu m$ flux densities. The two major results from this preliminary analysis concern the sub-mm background and the star-formation density in the early Universe. These are discussed in turn.

2.1 Resolving the submillimetre background

A P(D) analysis indicates the flux density distribution is matched reasonably well by a source density of about 7000 deg$^{-2}$ brighter than 1 mJy, which corresponds to the observed density of brighter sources, extrapolated with a Euclidean count slope, with the major caveat that this number assumes an unclustered source distribution. The counts must continue to flux densities somewhat fainter than 1 mJy, but the present data do not have the sensitivity to estimate where the inevitable break from the Euclidean slope occurs. This is best constrained by asking at what flux density the extrapolated count exceeds the submm background. By summing the flux densities in table 1, a lower limit to the background contributed by discrete submm sources of 20 mJy/5.6 arcmin$^2$ is found, equivalent to $\nu I_\nu = 1.5 \times 10^{-10}$ Wm$^{-2}$sr$^{-1}$, or approximately half the FIRAS background estimate. There is, however, evidence in our data, specifically by continuing the deconvolution until the residual noise is statistically symmetric, or using the cumulative counts to 1 mJy derived above, that the true background contributed by discrete sources may be up to a factor of two higher than this, essentially identical to the original FIRAS estimate, and consistent with more than 50% of the revised background estimate at 850$\mu m$ which suggests $\nu I_\nu = 5.0 \pm 4 \times 10^{-10}$ Wm$^{-2}$sr$^{-1}$. The faint counts must therefore flatten by a flux density of about 0.3 mJy, otherwise even this background estimate would be exceeded.

2.2 The redshift distribution of sub-mm sources in the HDF

A comparison of the typical spectral energy distribution for starburst galaxies with the detections (or upper-limits) of the submm HDF sources at 7, 15, 450 and 850 $\mu m$, and at 1.4 and 8.5 GHz (see and references therein) offers a powerful test of whether the submm sources are likely to be associated with high or low redshift galaxies. When combined with the calculation of the chance probability that the submm source is, in turn, associated with each of the nearby
Table 1: Positions and flux densities for the 5 most reliable sub-mm sources in the HDF with $S_{850} > 2$ mJy. The photometric redshifts based on the most likely optical counterparts [12]. Star-formation rates calculated from rest-frame UV (2800Å) and FIR (60 μm) luminosities are also given. An Einstein-de-Sitter cosmology is assumed.

| Source    | RA (J2000) | Dec (J2000) | $S_{850, μm}$ (mJy) | $z_{\text{est}}$ | $\log_{10} L_{\text{FIR}}$ ($h^{-2}L_{\odot}$) | SFR ($h^{-2}M_{\odot}yr^{-1}$) |
|-----------|------------|-------------|---------------------|------------------|-----------------------------------------------|-------------------------------|
| HDF850.1  | 12 36 52.32| +62 12 26.3 | 7.0 ± 0.4           | 3.4              | 12.15                                         | 0.7                           | 311                           |
| HDF850.2  | 12 36 56.68| +62 12 03.8 | 3.8 ± 0.4           | 3.8              | 11.87                                         | 0.2                           | 161                           |
| HDF850.3  | 12 36 44.75| +62 13 03.7 | 3.0 ± 0.4           | 3.9              | 11.76                                         | 0.1                           | 127                           |
| HDF850.4  | 12 36 50.37| +62 13 15.9 | 2.3 ± 0.4           | 0.9              | 11.83                                         | 0.3                           | 142                           |
| HDF850.5  | 12 36 51.98| +62 13 19.2 | 2.1 ± 0.4           | 3.2              | 11.64                                         | 0.3                           | 95                            |

The redshifts of the sub-mm sources, based on the suggested optical identifications, are consistent with the expectation that the galaxies detected in the 850μm survey of the HDF down to a flux limit $S_{850, μm} = 2$ mJy should be dominated by objects at redshifts $z \geq 1$. Given this, and the flat flux-density–redshift relation between $z = 1$ and $z = 10$, the dust-enshrouded SFRs (assuming that heating of the dust by an obscured AGN is insignificant) of the 5 brightest galaxies can be robustly estimated despite their imprecise redshifts. By summing the FIR SFRs and dividing by the appropriate cosmological volume, a first, conservative estimate of the level of dust-enshrouded star-formation rate in the high redshift Universe can be made using observations that are insensitive to the obscuring effects of dust. For illustrative purposes, it is assumed that four of the five sources lie in the redshift interval $2 < z < 4$, in which case a lower-limit to the dust-enshrouded star-formation rate density is $0.21 hM_{\odot}yr^{-1}Mpc^{-3}$ (assuming $q_0 = 0.5$) at $z \simeq 3$. This datum is compared in figure 1 with the optically-derived star-formation history of the Universe [3], the dust-corrected star-formation history predicted from the evolution of radio-loud AGN [15] and that inferred from the metal-production rate as determined from the observed column densities and metallicities in QSO absorbers [16].

This unique submm survey of unprecedented sensitivity has identified a population of high-redshift dusty starburst galaxies which contribute a significant fraction of the extragalactic submm background. These data also suggest that a significant fraction (> 90%) of the star-formation activity in the early Universe may have been missed in previous optical studies. Four of the five brightest submillimetre sources in the HDF alone provides a density of dust-enshrouded star-formation at $z > 2$ which is at least a factor of $\simeq 5$ greater than that deduced from Lyman-limit systems [8]. The extent to which even this is an under-estimate depends on the number of sources fainter than $S_{850} = 2$mJy at comparable redshift.

The immediate challenge is therefore to determine the true redshift distribution of the submm sources, in particular to confirm that galaxies detected in the deepest submm surveys lie at $z > 1$. This can be achieved by making millimetre interferometric measurements, with sub-arcsec positional errors, of the brightest sub-mm sources, and subsequently obtaining optical/IR spectroscopic redshifts of their unambiguously identified optical, IR or radio counterparts.
Figure 1: The global star-formation history of the Universe. Traditionally the mean co-moving rate of formation of stars in the Universe, $d\rho_{\text{stars}}/dt$, has been measured from the total UV luminosity density of galaxies. At $z < 1$, this was measured by the Canada-France Redshift Survey of Lilly et al. [1], and at higher redshifts from the optical HDF data [3]. The zero-redshift datum was inferred from local emission-line galaxies [4]. The shaded region shows the prediction (assuming $h = 0.65$) due to Pei & Fall [16] who argued using the observed column densities in QSO absorbers, plus the low metallicities in these systems, that the star-formation rate must have peaked between $z = 1$ and $z = 2$. The solid line illustrates what would happen if the star-formation rate tracked the total output of radio-loud AGN [15]. Based on the evidence which indicates that four of the five brightest sub-mm HDF sources lie in $2 < z < 4$, we infer a rate about 5 times higher than that obtained by Madau [3], but in good agreement with the external predictions of the rate at these epochs.

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