Unveiling Dust-enshrouded Star Formation in the Early Universe: a Sub-mm Survey of the Hubble Deep Field

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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 faintest optical images are insensitive. We present the deepest sub-mm survey of the sky to date, taken with the SCUBA camera on the James Clerk Maxwell Telescope and centred on the Hubble Deep Field. The high source density found in 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. We give positions and flux densities for these, and furthermore show using multi-frequency photometric data that the brightest sources in our map lie at redshifts $z \approx 3$. These results lead to integral source counts which are completely inconsistent with a no-evolution model, and imply that massive star-formation activity continues at redshifts $> 2$. The combined brightness of the 5 most secure sources in our map is sufficient to account for $30 \sim 50\%$ of the previously unresolved sub-mm background, and we estimate statistically that the entire background is resolved at about the 0.3 mJy level. Finally we discuss possible optical identifications and redshift estimates for the brightest sources. One source appears to be associated with an extreme starburst galaxy at $z \approx 1$, whilst the remaining four appear to lie in the redshift range $2 \leq z < 4$. This implies a star-formation density over this redshift range that is at least five times higher than that inferred from the ultraviolet output of HDF galaxies.
Understanding Star-Formation at High Redshift

Recent years have seen the first meaningful attempts to determine the global star-formation history of the Universe, using the combined leverage provided by deep redshift surveys (e.g. the Canada France Redshift Survey\(^1\)) reaching \(z \simeq 1\), and the statistics of Lyman-limit galaxies\(^2\) at higher redshifts in, for example, the Hubble Deep Field (HDF)\(^3\).\(^4\).\(^5\). The results\(^6\) imply that the star-formation and metal-production rates were about 10 times greater at \(z \simeq 1\) than in the local Universe, that they peaked at a redshift in the range \(z \simeq 1 \rightarrow 1.5\) and that they declined to values comparable to those observed at the present day at \(z \simeq 4\).

This conclusion, derived from optical-UV data, may however be misleading, because the absorbing effects of dust within distant galaxies undergoing massive star-formation may have distorted our picture of the evolution of the high-redshift Universe in two ways. First, the star-formation rate (SFR) in known high-redshift objects is inevitably under-estimated unless some correction for dust obscuration is included in deriving the rest-frame UV luminosity. Second, it is possible that an entire population of heavily dust-enshrouded high-redshift objects, as expected in some models of elliptical galaxy formation\(^7\), have gone undetected in the optical/UV surveys. The extent of the former remains controversial\(^8\).\(^9\).\(^10\).\(^11\) while the possibility of the latter has until now been impossible to investigate.

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 steep spectral-index of this emission longward of the peak, at \(\lambda \simeq 100 \mu m\) in the rest-frame, results in a large negative K-correction which is sufficient at sub-mm wavelengths to offset the dimming of galaxies due to their cosmological distances. Consequently the flux density of a galaxy at \(\lambda \simeq 800 \mu m\) with fixed intrinsic FIR luminosity is expected to be roughly constant at all redshifts in the range \(1 \leq z \leq 10\).\(^12\).\(^13\).\(^14\).

This ease of access to the young Universe has already been exploited through successful pointed sub-mm observations of known high-redshift sources including lensed objects (IRAS F10214+4724\(^15\) and the Cloverleaf quasar\(^16\)), radio galaxies\(^14\).\(^17\).\(^18\) and quasars\(^19\).\(^20\). These studies have demonstrated the potential of sub-mm cosmology and have shown that in at least some high-redshift galaxies, dust-enshrouded star-formation is proceeding at a rate of \(\gg 100 M_\odot yr^{-1}\), substantially greater than the more modest star-formation rates (e.g. on average \(\sim 1 - 5 h^{-2} M_\odot yr^{-1}\)) displayed by Lyman-break galaxies\(^3\).

With the recent commissioning of the sensitive sub-mm array camera SCUBA on the JCMT\(^21\) it is now possible to conduct unbiased sub-mm selected surveys\(^22\) 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 describe the first results from an ultra-deep sub-mm
survey centred on the HDF.

A Sub-mm Survey of Hidden Starformation in the Hubble Deep Field

Recent ISOCAM observations of the HDF at 6.7 μm and 15 μm have confirmed that the strong
evolution seen in the IRAS galaxy population at low redshifts\textsuperscript{23,24} continues out to redshifts of
order unity\textsuperscript{25,26}. Such mid-infrared studies can, however, provide no constraints at higher redshift.
In contrast an 850 μm 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. In particular, a SCUBA survey of the HDF complete to a flux density limit \( S_{850 \mu m} > 2 \) mJy would be expected to detect \(< 0.1 \) galaxies if there is no cosmic evolution, \(< 1 \) galaxy if the
evolution mirrored the Madau curve\textsuperscript{4}, but at least 2 sources if the number density and luminosity of
infrared starburst galaxies continued to evolve strongly out to \( z \simeq 2 \), and substantially more sources
with \( z > 2 \) if the population continued to evolve or stayed constant at higher redshifts\textsuperscript{7,12,27,28,29}.

We chose to centre this deep 850 μm survey on the HDF, not only because the SCUBA field of
view of \( \simeq 6 \) arcmin\(^2\) is well matched to the area of the HDF, but also to maximise the possibility
of finding optical/IR/radio counterparts and redshifts for any sub-mm sources which are detected.
Currently there exist over 20 spectroscopic redshifts for galaxies at \( z > 2 \) within the HDF, while
the availability of deep photometric data\textsuperscript{30} in the \( U_{300} \), \( B_{450} \), \( V_{606} \) and \( I_{814} \) bands facilitates the
estimation of photometric redshifts for other galaxies in the field.

Simultaneous diffraction-limited images of the HDF at 850 μm and 450 μm were taken with
SCUBA\textsuperscript{21} on the 15-m James Clerk Maxwell Telescope. A total of 50 hours integration between
January 5th and February 13th 1998 were centred at 12\textsuperscript{h} 36\textsuperscript{m} 51\textsuperscript{s} \cdot 20 + 62\textdegree 12\textquoteleft 52	extquoteright \cdot 5 (J2000) with
occasional offsets 25 arcsec south, east and west to aid the discrimination of real and spurious
sources. The sub-mm data were taken under exceptional atmospheric conditions, with a median
850 μm sky opacity \( \tau_{850 \mu m} = 0.16 \). Sky subtraction was performed using on-array chopping in
Right Ascension in order to minimise the chop throw (important for accurate sky subtraction), to
maximise the reclaimable signal-to-noise ratio for detected sources, and to minimise the number
of negative off-beams arising from unknown sources well outside the primary field of view. We
experimented with chopping in azimuth, but, at least at the declination of the HDF, this yielded
no significant noise improvement over chopping in RA. Finally, to ensure that no significant source
would be missed due to an unfortunate coincidence with the off-beam of another brighter source,
the length of chop throw was varied, approximately half the observations (29 hr) adopting an RA chop-throw of 30 arcsec, and the remainder (21 hr) an RA chop-throw of 45 arcsec. As discussed below, this approach proved invaluable both for source confirmation, and for the separation of real and confused sources. The 850$\mu$m data, with an angular resolution of 14.7 arcsec FWHM, covers an area of approximately 9 arcmin$^2$ and, due to the variation in the density of bolometer samples across the map, has a noise at the periphery approximately double its value at the map centre. The 850$\mu$m image in Figure 1 shows a circular field, within a radius of 100 arcsec from the map centre, and reaches a $1\sigma$ noise level of 0.45 mJy/beam. This image represents by far the deepest sub-mm map ever taken.

**Sub-mm source extraction and confusion**

Because the noise increases with radius from the map centre, sources were only sought within the central 80 arcsec radius of the image. The map shown in Figure 1 displays 58 distinct peaks, the majority of which are noise. For Gaussian filtered white noise, 1% of the peaks exceed 3.3$\sigma$ in amplitude$^{31}$, and so a flux density of 1.5 mJy (at the map centre) is the practical detection threshold for real sources; the map contains 7 such objects. The use of two different chops and the effect of telescope nodding is to produce a convolving beam with four negative sidelobes. The signature of a source is therefore very different from noise, and this fact can be used to identify real sources and to deconvolve the map down to some flux density limit. Deconvolution also allows the flux in the sidelobes of a source to be reclaimed, thereby enhancing the signal-to-noise ratio of the detected sources. In order to investigate whether these peaks correspond to single, or blended sources, simulations of random source distributions with plausible number counts have been carried out. The 14.7-arcsec beam is sufficiently broad that an ideal noise-free map would in fact never contain more than about 20 peaks within the 5.6 arcmin$^2$ map, independent of the true density of sources. Alternatively, the observed source density is about one source per 12 beam areas; both arguments indicate that source confusion must become important at the limit of our 850$\mu$m map.

It is thus possible that at least some of the apparent sources in the map could consist of emission from more than one object, and this is a particular concern for the weaker sources with $S_{850\mu m} \simeq 2$ mJy. One way of isolating such cases is optical identifications, as discussed below; if there is only a single candidate identification, the source cannot be a blend, since each member of the blend would have a separate optical counterpart.

Another approach is to note that confusion is only a serious problem when there is a blend of one or more sources of similar flux, and that in such cases the apparent source will usually
be significantly broader than the telescope beam. This breadth means that the apparent source position will be less stable under the addition of noise than if the source is dominated by a single unresolved object. We have therefore taken the conservative approach of identifying sources in the full data-set that appear in both the 30-arcsec and 45-arcsec chop images, and only keeping those whose positions agree to better than 3 arcsec. Tests on simulated source fields with realistic number counts show that this procedure should succeed in giving a clean sample of the sources brighter than 2 mJy in the central 80 arcsec radius of the image, each dominated by a single object. The positions of these 5 sources are given in table 1, together with their 850-\(\mu\)m flux densities.

The simultaneous 450 \(\mu\)m image covers 75\% of the useful area mapped at 850 \(\mu\)m and, despite the excellent observing conditions, which resulted in a 1\(\sigma\) rms noise signal of 7 mJy/beam at 450 \(\mu\)m, no significant detections were obtained.

**Number Counts and the Sub-mm Background**

The map shown in Figure 1 can be used to determine the form of the number counts at 850 \(\mu\)m fainter than the limit of 2 mJy at which individual sources can be selected with some confidence. Fainter sources combine to raise the rms fluctuations in the map beyond what is expected purely from noise. There is a long tradition in radio and X-ray astronomy of extracting faint counts from such information using ‘\(P(D)\)’ analyses\(^{32}\), although the present dataset is unusual in that both random noise and confusion noise are of similar amplitude. The approach adopted here is to focus upon the distribution of signal-to-noise ratios for the peaks of the map in Figure 1 (i.e. the distribution of fluxes for all apparent ‘sources’). By generating synthetic maps with different number counts, it is possible to estimate what range of true counts is consistent with the observed distribution.

We have not explored the full parameter space, but some examples are illustrated in Figure 2. Empirically, it is clear that there is an excess of peaks in the range 0.8 to 1.5 mJy, and this requires a substantial density of sources at about this flux-density level. The observed peak 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. If in fact the faint sub-mm sources are high-redshift starbursts, it is not implausible that they are strongly clustered on scales of several arcsec\(^{33,34}\). For a given surface density of sources, this increases the background fluctuations and so the above figure should probably be treated as an upper limit.
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 background. By summing the flux densities in Table 1, a lower limit to the background contributed by discrete sources of 20 mJy/5.6 arcmin$^2$ is found, equivalent to to $\nu I_\nu = 1.5 \times 10^{-10}$ Wm$^{-2}$sr$^{-1}$, or approximately half the background estimate reported by Puget et al.$^{35}$. 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 estimate of Puget et al., and consistent with more than 50% of the revised background estimates at 850 $\mu$m$^{36,37}$ which suggest $\nu I_\nu = 5.0 \pm 4 \times 10^{-10}$ 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.

**Photometric Observations, Spectra and Redshift Estimation**

Additional photometric observations during February 1998 at the centroid position of HDF850.1 confirmed the detection of the brightest sub-mm source with detections at 1350 $\mu$m of 2.1±0.5 mJy and at 850 $\mu$m of 7.0±0.4 mJy. These data, together with a 450 $\mu$m 3$\sigma$ upper limit of 21 mJy/beam provide a robust photometric estimate of the redshift of the source. In Figure 3 the expected flux density ratios at sub-mm and mm-wavelengths are plotted as a function of redshift for a range of models, typical of dusty, starforming galaxies, which are consistent with the observed optical to sub-mm spectra of Arp220, one the most heavily enshrouded local starburst galaxies$^{38,39}$, and the high-z starburst/AGN IRAS F10214+4724. The relevance of these models to galaxies in the high-z universe is reinforced by noting that the measured sub-mm and mm-wavelength flux density ratios of high-z AGN$^{14,40}$ lie close to or within the bounds of the models.

The photometric redshift for HDF850.1, determined from the 1350/850 $\mu$m flux density ratio, lies within the range 2.5 < z < 9. This strong constraint is supported by its non-detection at 450 $\mu$m which provides an upper limit to the 450/850 $\mu$m flux density ratio and hence a lower limit to its redshift of z > 3. Less stringent, but similar high redshift limits can be estimated for all sub-mm sources detected in the HDF by arguing that their non-detection at 15 $\mu$m at a 3$\sigma$ level of $\sim 20 \mu$Jy (Oliver et al. – in preparation) implies a lower limit of z $\sim$ 2 for sources at 850$\mu$m brighter than 2 mJy, assuming a starburst galaxy model$^{38}$, or z > 1.5 assuming the observed SED of the extreme starburst galaxy Arp 220. The radio-FIR correlation$^{41}$ yields lower limits of z = 1.75 and
$z = 2.75$ respectively for 2 mJy and 7 mJy sources detected at 850 $\mu$m, but not detected at 8.5 GHz at a $5\sigma$ flux limit of 9 $\mu$Jy. The above data demonstrate that deep sub-mm surveys provide an efficient means of identifying a population of star-forming galaxies at redshifts > 2.

Optical associations with sub-mm sources in the HDF

Given the rest-frame optical-FIR ratios typical of luminous starburst galaxies, the high-redshift SCUBA-selected galaxies are not necessarily expected to be present in the optical HDF, despite its depth. Nevertheless, we briefly discuss in turn plausible associations for the 5 most secure sub-mm sources in the HDF (see Figure 4), estimating photometric redshifts $z_{\text{ph}}$, for those galaxies without spectroscopic redshifts extended to include limits where galaxies are not detected in all four HDF bands.

Our approach is as follows. For each SCUBA source, we have considered as a potential optical counterpart all galaxies detected in the HDF whose distance from the SCUBA source lies within the 90% confidence limit of the sub-millimetre source position listed in Table 1. For each candidate we have then calculated the probability that a galaxy with such an optical magnitude (or brighter) could lie so close to the SCUBA position by chance, and also the probability that a galaxy with the observed redshift (or higher) could lie so close to the SCUBA position by chance. Note that these probabilities are often substantially higher than the raw Poisson probabilities. This is due to the combined effect of the rather large uncertainty in the SCUBA positions, and the high surface density of galaxies at the limit of the optical HDF image, which together essentially guarantee that (with the exception of HDF850.1) every SCUBA source will have at least one optical identification candidate at the limit of the HDF image. Finally we have investigated whether any of the apparently most probable optical identifications can in fact be clearly rejected on the basis of the SED constraints discussed above.

**HDF850.1** As shown in Fig. 4, this source lies 1.0 arcsec from galaxy 3-577.0 in the optical HDF catalogue which has a tentative spectroscopic redshift of $z = 3.36$ (ref. 45), and which has been claimed to be gravitationally lensed by the foreground $I_{814}(AB) = 24$ elliptical galaxy 3-586.0 which lies at $1.0 \leq z \leq 1.2$ (refs. 43,47,48). More recently, a $3.5\sigma$ detection ($6.3\mu$Jy) at 8.5-GHz source has been associated with 3-586.0 (ref. 42). Based on its magnitude the probability that 3-577.0 is a chance association with HDF850.1 is 0.33, while based on its redshift (which we estimate is $z_{\text{ph}} = 3.1$) the probability (calculated from the surface density of $z_{\text{ph}} > 3$ galaxies in photometric redshift catalogues) is only 0.20. For 3-586.0 the probabilities are in fact comparable ($0.29$ and $0.49$ respectively), but the non-detection of HDF850.1 at 15 $\mu$m ($S(3\sigma) < 23\mu$Jy) is strongly...
inconsistent (by almost two orders of magnitude) with the observed SEDs of any known galaxy (including Arp 220) if placed at the 'low' redshift of 3-586.0. Moreover, as discussed above, the mm/sub-mm flux ratios also indicate that $z > 2.5$, and Figure 5 shows that the observed spectrum of HDF850.1 agrees well with that expected for a starburst galaxy at redshift $z \sim 3$. We note that the random probability of being 2 arcsec from one of the radio sources$^{42}$ is only 0.03. If the radio source really is associated with 3-586.0, and HDF850.1 with 3-577.0, then these seemingly incompatible probabilities are best explained by assuming that 3-577.0 is indeed being gravitationally lensed by 3-586.0, thereby amplifying its rest-frame FIR flux, and increasing its chances of being detected at 850 $\mu$m by SCUBA. The amplification would, however, need to be fairly substantial to explain the statistics, implying a massive lens; 3-586.0 may be the only visible member of a fainter group of galaxies.

**HDF850.2** lies just beyond the edge of the HDF making an assessment of possible optical associations difficult since the $I_{814}$ band Hubble Flanking Field (HFF) image only reached a depth of $\sim 25$ mag. HDF850.2 is 4.3 arcsec from the $z_{\text{ph}} = 3.8$ galaxy 3-962.0 on the edge of the HDF, but based on its magnitude the probability that 3-962.0 is a chance association with HDF850.2 is 0.63, while based on its redshift the probability is 0.46. As can be seen in Figure 4, there does appear to be a more convincing, but also very faint candidate identification within the HFF, but at present we possess little useful colour information for this object. Therefore, while the non-detection at 15 $\mu$m implies a flux density ratio $S(850\mu m/15\mu m) > 190$ consistent with the SED of a starburst galaxy at $z > 2$, we are unable to make an unambiguous optical association.

**HDF850.3** lies only 1.3 arcsec from 1-34.2 which is an asymmetric galaxy with $I_{814}(AB) = 24.5$ for which we estimate $z_{\text{ph}} \sim 1.95$. This is a moderately convincing identification since based on its magnitude the probability that 1-34.2 is a chance association with HDF850.3 is only 0.29 (although based on its redshift the probability is 0.52) and its estimated redshift is consistent with a non-detection or marginal detection at 15 $\mu$m. The next nearest object is 1-34.0, a $I_{814}(AB) = 21$ galaxy at a distance of only 1.5 arcsec. For this galaxy the random probabilities are 0.12 and 0.60 respectively but with a tentative spectroscopic redshift of 0.49, and photometric redshift estimates in the range $0.26 \leq z_{\text{ph}} \leq 0.68$, this object can be confidently rejected as a possible identification given its non-detection at 15 $\mu$m, 450 $\mu$m and radio wavelengths. We note also that 1-34.0 shows no obvious signs of starburst activity at optical wavelengths, and appears to be a relatively undisturbed spiral galaxy. Should the identification with 1-34.2 prove to be erroneous we note for completeness that two $z_{\text{ph}} \sim 3.9$ galaxies, the nearer being 1-27.0, and the further 1-31.0, lie within 4 arcsec of HDF850.3. Based on magnitude the probability that these are chance associations is 0.63, while based on redshift it is 0.3.
HDF850.4 lies less than an arcsec from 2-339.0, an $I_{814}(AB) = 23$ galaxy for which photometric redshifts have been determined in the range 0.74-0.88 (refs. 43,47,48). This is a convincing identification since based on its magnitude the probability that 2-339.0 is a chance association with HDF850.4 is only 0.07 (based on its redshift the probability is 0.44). Moreover, this is the one case for which the 850$\mu$m source can be plausibly associated with an ISOCAM detection at 15$\mu$m, which yields a flux density ratio $S(850/15\mu m) \sim 16$. This is in fact exactly the value expected from the observed SED of Arp220 if placed at $z \simeq 1$. This supports an identification with 2-339.0, and emphasises the usefulness of constraining the redshift using the $S(850/15\mu m)$ ratio. Furthermore we note that this optical galaxy is clearly disturbed, as would be expected for an extreme starburst galaxy, providing further circumstantial evidence that it is the correct optical identification. However, should this identification prove erroneous we note that there are 3 galaxies (2-294.0, 2-315.0, 2-319.0) with $z_{ph} > 3$ within 3.5 arcsec of HDF850.4.

HDF850.5 is located in a sparsely-populated region of the HDF, but is only 0.9 arcsec away from the $I_{814}(AB) \sim 29$ galaxy 2-426.0, for which we estimate a photometric redshift of $z_{ph} = 3.2$. This is a moderately convincing identification; based on its magnitude the probability that it is a chance coincidence is 0.46, but based on its redshift it is a more impressive 0.16. This high-redshift association is consistent with the lack of a 15$\mu$m detection at that position, but we note the difficulty of estimating photometric redshifts for such faint HDF galaxies. Finally we note that 7 other faint ($I_{814}(AB) > 27.5$) galaxies lie within 3.5 arcsec of HDF850.5 (see Figure 4), but these objects are significantly more likely to be chance coincidences, and in any case all also have photometric redshifts $z_{ph} > 2$.

In summary, HDF850.4 appears to be associated with a disturbed starburst galaxy at $z_{ph} \simeq 1$, HDF850.3 with an asymmetric galaxy at $z_{ph} \simeq 2$, and HDF850.1 and HDF850.5 have relatively unambiguous associations with galaxies at $z_{ph} \simeq 3$. For HDF850.2 we find a possible identification within the HDF at $z \simeq 4$, and an alternative (also faint) candidate in the HFF which can be reasonably expected to lie at $z > 2$. Finally we note that we are clearly unable to rule out the possibility that the true optical counterparts of a few of these sources may be too faint for detection even in the HDF.

Dust masses, star-formation rates and star-formation density at high redshift

The photometric redshifts and suggested optical identifications for the sub-mm sources are consistent with the expectation that all galaxies detected in the 850$\mu$m survey of the HDF down to a flux limit $S_{850\mu m} = 2$ mJy should have redshifts $z \geq 1$. Given this, and the flat flux-density–redshift
relation between \( z = 1 \) and \( z = 10 \), the dust-enshrouded SFRs and the dust masses for all 5 reliable sources can be estimated, independent of their precise redshifts. The results are given in table 2, and indicate that these sources are extremely dusty and have SFRs, when determined from the sub-millimetre data, that are similar to, or exceeding, that of the local ultraluminous starburst galaxy Arp220. Note that the calculated SFRs are sensitive to the assumed IMF and stellar mass-range (and can in the extreme increase and decrease by a factor of \( \sim 3 \)). More striking is the comparison of the FIR SFRs with those calculated from the rest-frame UV luminosities. The FIR method gives SFRs on average a factor \( \sim 300 \) larger. It has been shown that optical SFRs, estimated from Balmer emission line luminosities in Lyman-break galaxies at \( z \sim 3 \), are larger than the UV SFRs by factors of 2-15. This upward correction, due to attenuation by dust\(^9,10\), still would require a further factor of \( \sim 50 \) to explain the higher FIR SFRs. A similar situation has been observed in the local universe where the ratio of FIR and \( \text{H} \alpha \) luminosities in ultra-luminous IR starburst galaxies (ULIRGs) is \( \sim 60 \times \) larger than that in disk galaxies\(^49\), suggesting that in young starbursts most OB stars are still deeply buried in their opaque parent clouds. The submillimetre sources we have seen are then quite typical of local ULIRGs, but their relevance to the overall cosmic star formation history depends on their space density.

The small uncorrected UV SFRs (< 1 \( h^{-2} \text{M}_\odot \text{yr}^{-1} \), table 2) for the optical counterparts of the submillimetre sources are reasonable, given that these galaxies are typically a few magnitudes fainter in the rest-frame UV, possibly due to greater dust obscuration, than the population of Lyman-break galaxies at \( z \sim 3.5 \) which have SFRs of \( \sim 2 h^{-2} \text{M}_\odot \text{yr}^{-1} \). Alternatively it may be that the less secure identifications are erroneous, and that some of the sub-mm sources may have true optical counterparts below the detection limit on the HST HDF image, and therefore probably at \( z \geq 5 \).

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 can be reasonably assumed that four of the five sources (all but HDF850.4) 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 \( h \text{M}_\odot \text{yr}^{-1} \text{Mpc}^{-3} \) (assuming \( q_0 = 0.5 \)) at \( z \simeq 3 \). This datum is plotted in figure 6, where it can be compared with the optically-derived star-formation history of the Universe\(^3,4\), the dust-corrected star-formation history predicted from the evolution of radio-loud AGN\(^50\) and that inferred from the metal-production rate as determined from the observed column densities and metallicities in QSO absorbers\(^51,52\).
If the redshift distribution extended beyond $z = 4$, the mean redshift would increase, but due to increased cosmological volume the star-formation rate density would decrease in such a way that the data would remain consistent with the curves shown in Figure 6. For example, assuming a redshift range $2 < z < 5$ yields a star-formation density of $0.16 \, h \, M_\odot \, yr^{-1} \, Mpc^{-3}$ at $z \simeq 3.5$.

Finally, we emphasize that the SCUBA datum plotted in Figure 6 is in fact rather robust. For example, should our proposed identification for HDF850.3 (1-34.2) prove to have a spectroscopic redshift significantly lower than $z = 2$, the impact on Figure 6 will be to lower the $z \simeq 3$ SCUBA datum by only 20%. However, the impact of even one of these sources lying at still higher redshift is rather dramatic; if one of the 2-3 mJy sub-mm sources we have detected actually lies at $z > 4$, this would yield a star-formation density of $0.1 \, h \, M_\odot \, yr^{-1} \, Mpc^{-3}$ in the redshift range $4 < z < 6$, thus keeping the star-formation density essentially constant out to $z \simeq 5$.

In summary, this deep submillimetre survey of the HDF demonstrates that a significant fraction (> 80%) of the star-formation activity in the high-redshift universe may have been missed in previous optical studies. Four of the five brightest submillimetre sources alone provide 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$^3$. 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.

This unique submillimetre survey of unprecedented sensitivity has identified a population of high-redshift dusty starburst galaxies which contribute a significant fraction of the extragalactic background at 850 $\mu$m. These observations, together with complementary wider, shallower submillimetre surveys, are now beginning to provide the first true measurement of the starformation history for the early universe, unhindered by the attenuating effects of dust. The challenge for the future is to follow up these observations, in particular those of the sub-mJy sources which at present can only be detected statistically.

It is now possible that some of these objects lie at $z > 5$, but demonstrating this will require the individual detection of these sources with sub-arcsec position errors. This will require both improved noise performance and higher spatial resolution in order to evade the confusion limit. Facilities such as the forthcoming generation of sub-millimetre arrays are ideally matched to these key programmes for astrophysical cosmology.
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Table 1. Positions and flux densities for the 5 most reliable sub-mm sources in the HDF with $S_{850} > 2$ mJy. The positions of these sources are reproduced from deconvolutions of both the 30-arcsec and 45-arcsec chopped images to within 3 arcsec. Positions given for each source were obtained from the average of the positions obtained using the independent SURF and IDL reductions. The quoted r.m.s. positional uncertainties were derived from the formula $\sigma_{\text{pos}} = \theta_{\text{beam}}/(2\text{S/N})$, where $\theta_{\text{beam}}$ is the FWHM of the beam and S/N is the signal-to-noise ratio of the source. A further 0.5 arcsec uncertainty was added in quadrature, to account for the standard error in absolute pointing derived from measured pointing offsets throughout the observations. Flux densities quoted are the average from 3 independent methods, all of which agreed to within the formal uncertainty. Absolute calibration is uncertain to 10%.

| IAU name          | RA (J2000)         | Dec (J2000)         | $S_{850\mu m}$ (mJy) |
|-------------------|--------------------|--------------------|----------------------|
| HDF850.1 J123652.3+621226 | 12 36 52.32 (±0.10) | +62 12 26.3 (±0.7)  | 7.0 ± 0.5            |
| HDF850.2 J123656.7+621204  | 12 36 56.68 (±0.20) | +62 12 03.8 (±1.4)  | 3.8 ± 0.7            |
| HDF850.3 J123644.8+621304  | 12 36 44.75 (±0.21) | +62 13 03.7 (±1.5)  | 3.0 ± 0.6            |
| HDF850.4 J123650.4+621316  | 12 36 50.37 (±0.23) | +62 13 15.9 (±1.6)  | 2.3 ± 0.5            |
| HDF850.5 J123652.0+621319  | 12 36 51.98 (±0.25) | +62 13 19.2 (±1.8)  | 2.1 ± 0.5            |

Table 2. Star-formation rates and dust masses of 5 most reliable sub-mm sources in HDF with $S_{850} > 2$ mJy. Column 2: Photometric redshifts based on the most probable optical associations. Column 3: $60\mu m$ luminosity determined from the starburst model of M82\(^{38}\) scaled to the observed 850\(\mu m\) flux densities. Columns 4,5: Star-formation rates calculated from rest-frame UV (2800 Å) and FIR (60\(\mu m\)) luminosities\(^{3,26}\). The UV flux densities at 2800Å are interpolated from the measured $I_{814}(AB)$ and $V_{606}(AB)$ magnitudes\(^{30}\). Column 6: Dust masses, assuming $\beta = 1.5$, T = 50 K\(^{15}\). An Einstein-de Sitter cosmology is assumed.

| source     | $z_{\text{est}}$ | $\log_{10} L_{60\mu m}$ | $\log_{10} \text{SFR} (h^{-2}M_\odot\text{yr}^{-1})$ | $\log_{10} M_{\text{dust}} (h^{-2}M_\odot)$ |
|------------|------------------|-------------------------|---------------------------------|------------------|
| HDF850.1   | 3.4              | 12.15                   | 0.7                             | 311              |
| HDF850.2   | 3.8              | 11.87                   | 0.2                             | 161              |
| HDF850.3   | 2.0              | 11.76                   | 2.0                             | 127              |
| HDF850.4   | 0.9              | 11.83                   | 0.7                             | 142              |
| HDF850.5   | 3.2              | 11.64                   | 0.3                             | 95               |
The 850µm SCUBA image of the HDF. The image shows a radius of 100 arcsec from the map centre (12^h36^m51.2^s +62°12'52.5'' - J2000) and is orientated with North upwards and East to the right. Primary flux calibration was performed using Uranus, with secondary calibration against a variety of AGB stars and compact HII regions. The absolute calibration uncertainty is < 10%. The data, taken in jiggle-map mode, were reduced in parallel using two wholly independent methods. The first reduction used the SCUBA User Reduction Facility (SURF v.1.2), whilst the second reduction was performed with a specially-written IDL pipeline. Both methods incorporate individual bolometer rms noise weighting in the map reconstruction. An iterative temporal deglitching and spatial sky subtraction was performed. The IDL maps were reconstructed using a noise-weighted “drizzling” technique and were in excellent agreement with the independent SURF reconstructions. Individual subsets of the data were also reduced using both techniques, including the production of separate images with 30 arcsec and 45 arcsec chop throws. The centre of the map contains a higher density of bolometer samples than the periphery. Consequently the noise is a function of position and this variation can be deduced exactly from the known jiggle pattern, and is approximated closely by a quadratic radial variation $\sigma \propto 1 + (r/90 \text{arcsec})^2$ in the central regions. In the SURF reduction, the noise has the statistical character of white noise filtered with a beam of FWHM 6 arcsec, with an rms of 0.65 mJy at the map centre. Convolution of the map reduces this noise, but possible confusion from faint sources means that it is preferable not to broaden the point-source response significantly. As a compromise, a further convolution with a 6-arcsec beam was applied, reducing the rms noise signal to 0.45 mJy at the map centre. The noise on the final map therefore has the character of white noise convolved with a beam of FWHM 8.5 arcsec. A signal-to-noise image is shown, allowing the significance of faint potential sources to be judged in a uniform manner, although it means that there is a tendency for more sources to be detected in the central regions. The analysis of sources was restricted to the central 80 arcsec radius. Because the observing strategy yields a point-source response with negative sidelobes at 0.25 of the peak, the map was CLEANED and restored with a 14.7 arcsec FWHM gaussian beam.

Figure 2. The raw integral number counts for the central 80 arcsec radius of the map in figure 1 is shown as the jagged solid line on this plot. The flux units here are signal-to-noise, but scaled to the flux units in the map centre. This uniform-noise representation allows a clear demonstration of sources in excess of the expectation for a pure noise field (dashed line) above about 0.8 mJy. Synthetic maps were made with the observed noise properties using a random distribution of sources having Euclidean counts down to a limit of 0.3 mJy (although the results are insensitive to this cutoff). The grey band shows the effect of varying the integral surface density at 1 mJy between 4000 and 10000 degree$^{-2}$.

Figure 3. An estimation of redshift using measured submillimetre flux densities. The hatched area shows the range of submillimetre flux density ratios as a function of redshift which are constrained by two extreme models of dusty, starforming galaxies (Arp220 and IRAS10214+4724) and are consistent with observations of high-z galaxies. The solid horizontal lines represent the measured flux ratios for HDF850.1 and, in the case of the S(1350/850 µm) ratio, the horizontal dotted lines represent errors of ±1σ on the observed ratio. The solid shading represents the parameter space satisfied by the photometric data for HDF850.1, including the non-detection at 450 µm, and illustrates that the redshift for HDF850.1 probably lies between 2.5 < z < 9.
Figure 4. Optical associations for the brightest five submillimetre sources in the HDF. The top-left panel indicates the approximate location, and orientation of each of the 10×10 arcsec $I_{814}$-band postage stamps shown in the following 5 panels. In each postage stamp the two large circles represent the 90% and 50% confidence limits on the sub-mm positional uncertainty, whilst a small circle (1 arcsec in diameter) has been used to mark the location of the most plausible optical association (or associations) for each SCUBA source (see text).

Figure 5. The observed optical–radio spectral energy distribution of HDF850.1. The solid circles represent the SCUBA 850 and 1350$\mu$m detections. Non-detections at 8.5 GHz$^{42}$, 450$\mu$m (this paper), 15 and 6.7 $\mu$m (Oliver et al. - in prep.) are shown as open diamonds. The solid squares indicate the optical fluxes in the $I_{814}$, $V_{606}$ and $B_{450}$ HST bands of the $z = 3.36$ galaxy 3-577.0, which is a plausible association for HDF850.1. A starburst galaxy model (solid curve)$^{38}$ has been redshifted to $z = 3.36$ and normalised to the 850$\mu$m flux density. An additional radio non-thermal synchrotron component (where $F_\nu \propto \nu^{-0.8}$) is scaled to the starburst model at 60$\mu$m using the radio-FIR correlation$^{41}$. The 15$\mu$m upper-limit is consistent with the model SED since the contribution from a rest-frame 3.3$\mu$m PAH feature, averaged over the ISOCAM LW3 bandpass, is insignificant.

Figure 6. The global star-formation history of the universe. Traditionally the mean comoving 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$^{56}$. The shaded region shows the prediction (assuming $h = 0.65$) due to Pei & Fall$^{52}$ 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$^{50}$. 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$^{50,51}$ of the rate at these epochs.
