Optical/near-IR galaxy counts

\( \nu I_\nu \) background (nW/m^2/sr)

wavelength (\( \mu m \))

COBE FIRAS/DIRBE
$S_{850} \text{ (mJy)}$

$3 \times 10^{12} h_{50}^{-2} L_\odot \text{ starburst}$

$\Omega_0 = 1$

$\Omega_0 = 0.3$

SCUBA 3$\sigma$ 8hr

redshift
plus one $I_{AB} = 23.4 \ z_{est} = 1.5$ (No $K$)
and four unidentified or insecure identification
Abstract

Deep surveys in the far-infrared and sub-millimetre wavebands are revealing a new phase of galactic evolution hidden by dust. Observations with SCUBA on the JCMT show that 25% of the COBE/FIRAS background at 850 µm is being produced by high luminosity sources (L ~ 3x10^{12} L_\odot) at high redshifts 0.5 < z < 3. These sources have an estimated redshift distribution that is broadly consistent with a global star-formation history that is similar to that inferred from optical observations. The sub-mm galaxies and optically selected galaxies are producing comparable quantities of stars. However, the sub-mm sources are doing so in systems that have luminosities an order of magnitude higher, and comoving densities an order of magnitude lower, than the optically selected galaxies. These high luminosity sub-mm sources are plausibly responsible for producing the spheroidal components of massive galaxies at z ∼ 2.

1. Introduction: Galaxy evolution and the NGST

The last few years have seen great progress in obtaining a first outline of the evolution of galaxies over a remarkably wide range of cosmic time, corresponding to redshifts 0 < z < 5.

Much of this progress can be summarized in the plot of ultraviolet luminosity density of the Universe with redshift (Lilly et al 1996, Madau et al 1996, 1998, Connolly et al 1997) shown frequently at this meeting. This plot suggests that the overall star-formation rate in the Universe rises quite rapidly to a peak in the 1 < z < 2.5 range and subsequently declines at higher redshifts. However, it should be appreciated that, even in terms of the observationally defined quantity L_{uv}(z) there are still significant uncertainties in the form of this diagram at the higher redshifts (see e.g. Sawicki et al 1997). Furthermore, in translating the luminosity density L_{uv}(z) into a star-formation rate there are additional substantial uncertainties regarding the effects of dust obscuration as well as the shape of the i.m.f.

Despite this clear progress, the relationship between the stars produced at different epochs and the present-day morphological components of galaxies remains ambiguous (the luminosity density plot completely suppresses the identity of individual galaxies). The evolution to z ∼ 0.8 appears to be primarily due to small galaxies with irregular morphology and to disk galaxies (see e.g. the morphological analyses of Brinchmann et al 1998 and Lilly et al 1998a). The nature of galaxies at z > 3 is still controversial (see e.g. Dickinson 1988, Trager et al 1997 and references therein), and very little is known about the nature of galaxies in the crucial intermediate redshift range 1.5 < z < 3. Two primary scientific goals of the NGST are to reveal the earliest generation of stars and galaxies at z >> 5 and to elucidate the main physical processes operating in the 1 < z < 5 range that led to the establishment of the Hubble sequence.

In particular, and as emphasized by Richard Ellis at this conference, the origin of the stars seen in the spheroidal components of galaxies is not well understood. There are inconclusive observational arguments both in favour of rapid and homogeneous spheroid formation at very high redshifts and in favour of formation through mergers spread over a broad range of epochs. These alternatives are often viewed as mutually incompatible, although the formation of the bulk of spheroid stars in highly dissipational mergers of gas-rich systems at high redshifts would...
combine the attractive features of both scenarios. A problem, however, with this scenario has been the lack of detection, up till now, of a substantial population of high luminosity star-forming systems with the high star formation rates ($10^2$–$10^3 \, M_\odot\,yr^{-1}$) required to produce spheroidal components of galaxies in dynamical timescales ($10^8 \, yr$).

But it should be stressed that, except for a few unusual objects, our view of the evolution of typical galaxies has come almost exclusively from studies of starlight in the optical and near-infrared wavebands. Very little has been known until recently about that component of stellar energy that emerges in the far-infrared waveband in the form of thermal emission from dust.

This is unfortunate, as studies of the local Universe indicate that between 30-40% of stellar energy emerges as thermally re-radiated dust emission (see e.g. Dwek et al 1998 and references therein). Furthermore, the recently detected far-IR/sub-mm background seen in the COBE data (Puget et al 1996, Hauser et al 1998, Fixsen et al 1998) has a $\nu I_\nu$ energy content that is as large or larger than the optical background that is obtained by integrating the galaxy number counts (see Fig 1). This indicates that dust continues to play a major role at high redshifts — it should be noted that any differences in the redshifts at which these backgrounds are produced will change their relative energy content only as $(1+z)$ — and that a half or more of the energy from stellar nucleosynthesis emerges in the FIR.

Understanding the nature and redshifts of the sources responsible for the far-IR/sub-millimetre background is therefore vital for an understanding of galaxy evolution. Fortunately, recent technical developments in space and on the ground are allowing us to begin to resolve this background and to identify faint far-IR and sub-mm sources. There has been recent progress with the ISO satellite at 15 $\mu$m and at 175 $\mu$m (see the contribution of Jean-Loup Puget in these proceedings). Observations at 15 $\mu$m are most sensitive to the hot dust component and to sources at redshifts $z \leq 1$, since at higher redshifts the passband is redshifted off the energy plateau at $\lambda < 7 \mu$m. Sources at higher redshifts are thus harder to detect and the calculation of bolometric output much more uncertain. Flores et al (1998b) have analysed deep ISO 15 $\mu$m images of the CFRS 1415+52 field and concluded that the star-formation rate estimated from the ultraviolet luminosity density should be increased by a factor of about 2 in the $0 < z < 1$ range. A much larger correction was obtained by Rowan-Robinson et al (1997) in their analysis of the HDF. The difference appears to stem largely from the assignment of spectral energy distributions to the detected sources. Flores et al (1998b) also drew attention to the fact that large amounts of star-formation were concentrated in a small number of luminous galaxies in the $0 < z < 1$ range.

In parallel, several groups are pursuing deep surveys in the sub-millimetre waveband at 450 and 850 $\mu$m with the SCUBA bolometer array (Gear et al 1998), on the 15m JCMT on Mauna Kea. In contrast to the situation at shorter wavelengths, the spectral energy distributions of galaxies in the sub-millimetre waveband rise sharply with frequency up to a peak in the 70-120 $\mu$m range and the k-corrections at 850 $\mu$m are thus extremely beneficial, even to very high redshifts. In fact, a given star-burst galaxy (with an effective dust temperature of around 30K and effective emissivity proportional to $\nu^{1.5}$) has a roughly constant observed flux density at 850 $\mu$m over the entire $0.5 < z < 6$ redshift range, especially if $\Omega = 1$ (see Fig 2). Observations at 850 $\mu$m are thus very sensitive to star-formation at very high redshifts.

2. Deep sub-millimetre surveys with SCUBA

Several groups based in the UK, Canada and Hawaii are therefore pursuing surveys of the sub-millimetre sky with SCUBA. The potency of this waveband was demonstrated by the initial results of Smail et al (1997), who detected lensed background sub-millimetre sources in the fields of rich clusters of galaxies. The brightest of these, with $S_{850} = 26 \, mJy$, was subsequently shown to be an AGN at $z = 2.8$ by Ivison et al (1998).

Our own program is a Canadian-UK collaboration aimed at surveying fields from the Canada-France-Redshift Survey (CFRS, Lilly et al 1995a, Le Fèvre et al 1995 and references therein). The CFRS fields not only have extensive redshift data available for galaxies with $I_{AB} < 22.5$, but also have a wealth of deep imaging data from the CFHT and HST, deep 7 and 15 $\mu$m maps taken with ISO (Flores et al 1998ab) and the VLA (Fomalont et al 1992, Hammer et al 1995b). The survey is not targeted at known objects and will ultimately cover most of the CFRS–0300+00 (Hammer et al 1995a) and CFRS–1417+52 fields (Lilly et al 1995b).

The first data in this program was obtained in January and March 1998 and some 20 arcmin$^2$ have been covered to a 3$\sigma$ limiting point-source sensitivity of between 2.7 – 3.0 mJy at 850 $\mu$m (see Eales et al 1998 for details). A total of 11 sources are detected at $S_{850} > 3 \, mJy$.

Our 11 sources yield a cumulative source count of $1980 \pm 600 \, deg^{-2}$ to $S_{850} = 3 \, mJy$ (Eales et al 1998). This is consistent with the smaller lensing sample of Smail et al (1997), corrected for the effects of lensing by the clusters, and with the five-source HDF sample
(3200 ± 1450 to 2 mJy) of Hughes et al (1998) and the two-source Hawaii sample (290-1900 deg² to 3 mJy) of Barger et al (1998). The 11 sources are responsible for approximately 22% of the COBE/FIRAS background at this wavelength (Puget et al 1996, Fixsen et al 1998).

Even with a 1.5m telescope, the beam size at 850 μm is 15 arcsec, so identifications of the sub-mm sources at other wavelengths must for now be based on probabilistic arguments. The probability that a member of a population with cumulative surface density \( n(<S) \) down to the flux density of the source, \( S \), is located a distance \( d \) from the nominal sub-mm position and yet be unrelated to the sub-mm sources is given by \( P = 1 - \exp(-\pi n d^2) \). Of our 11 sources, 7 have identifications with \( P < 10\% \) and four of these have \( P < 1\% \).

The identifications span a very wide range of redshifts. One source is an \( I_{AB} = 16 \) spiral galaxy with spectroscopic redshift \( z = 0.08 \) and two more sources are securely identified with CFRS galaxies with previously measured redshifts of \( z = 0.55 \) and \( z = 0.66 \). The remaining four identifications have colours (generally \( VIK \)) from which we estimate redshifts of approximately 0.8, 1.5, 2.0 and 2.5 (Fig 3). Therefore at least 3, and probably 4, of the 11 identifications have \( z < 1 \). This is counter to the expectation of Hughes et al (1998) that all sources in such surveys would be at \( z > 1 \). The \( I_{AB} \) magnitudes of the identifications correlate well with the redshifts estimated from their colours and indicate that these are generally luminous optical galaxies with roughly \( L^* \) optical luminosities (Fig 4).

For the remaining four sources, there are in most cases plausible identifications with \( I_{AB} \geq 24.5 \), but the probability of a chance projection is sufficiently high (\( P \geq 10\% \)) that these can not be claimed as secure identifications. It is quite likely that these galaxies lie at \( z > 2.5 \). Many of these possible identifications are detected at U or B, suggesting redshifts \( z \geq 3-4 \), but the possibility that the sub-mm emission comes from other, fainter or higher redshift, galaxies cannot be excluded for these last four sources.

The morphologies of the identified galaxies on our HST F814W images range from normal or disturbed-looking disk systems to obvious dramatic merger events (Fig 5). Many have strong tails and evidence for multiple nuclei.

For all sources we have measurements or limits to the 450 μm flux densities and visual magnitudes, and for those in the CFRS–1417+52 field, we also have measurements or limits at 7 and 15 μm (Flores et al 1998a,b) and at 5 GHz (Fomalont et al 1992, Hammer et al 1995). The spectral energy distributions thus defined are consistent with the spectral energy distributions of highly obscured starburst galaxies (from Schmitt et al 1997) at the redshifts that have either been spectroscopically measured or that have been estimated from the colours. Within the CFRS–1417+52 field, the relationships between samples of objects selected at different wavelengths also follow expectations. For example, the two μJy-level radio sources that were detected by SCUBA have the steepest radio spectra (consistent with star-formation) whereas the remaining four radio sources in our surveyed area have flat or inverted radio spectra (indicative of AGN). Likewise, the SCUBA sources not detected by ISO at 15 μm all have high inferred redshifts but the ISO sources not detected by SCUBA all have low redshifts \( z \leq 1 \).

The redshift distribution implied by our identifications is thus broad (Fig 6), extending from very low \( z \) to redshifts that are likely to be in excess of \( z = 3 \). Even if the \( z = 0.08 \) galaxy is discounted as a fluke, the redshift distribution is roughly flat between 0.5 < \( z < 3+ \). The smaller samples of Hughes et al (1998) and Barger et al (1998) appear to be broadly consistent with our redshift distribution. The lensed sample of Smail et al (1998) does not have redshift estimates but appears to have a similar distribution in \( I_{AB} \) magnitude.

3. High luminosity sources at high redshifts: the hidden phases of galaxy evolution and the relation to the optical picture

Unfortunately, models for the 850 μm sky are still quite uncertain, being generally based (e.g. Blain and Longair 1993, Eales & Edmunds 1997) on extrapolations from the IRAS 60 μm population (a factor of 13 in wavelength). In the near future, SCUBA observations of nearby optically-selected and IRAS-selected galaxies (e.g. Dunne et al 1998) will lead to a big improvement in the models. Nevertheless, it is clear that the observed counts are in excess of “no evolution” predictions by two orders of magnitude in number at a given flux density, but only by an order of magnitude or so in terms of flux density at a given number density (Eales et al 1998).

Clearly a key questions is to what extent the implied evolution in the sub-mm population is similar to or different from that inferred from optical studies.

First, it should be noted that the sub-mm counts can in fact be successfully matched (Eales et al 1998) by a local 850 μm luminosity function undergoing luminosity evolution such that the luminosity density has the same redshift dependence as in the optical (Madau et al 1996). Furthermore, this model also reproduces (Eales et al 1998) the spectral shape of the
FIRAS background if the effective emissivity of the population is nearer \( v^1 \) than \( v^{1.5} \) (but see Jean-Loup Puget’s contribution to these proceedings).

Second, the limited redshift information currently available is also consistent with this hypothesis. An interesting way to look at this is in terms of the redshift distribution of the light in the 850 \( \mu m \) background. For the case of a population of star-forming galaxies whose spectral energy distribution is flat (i.e. \( f_{\nu} \propto \nu^0 \)), it is easy to show (Lilly and Cowie 1987) that the cumulative distribution in redshift of the light in the background is identical to the cumulative distribution in redshift of the production of stars in the Universe. This result is formally independent of the cosmology, the nature of the star-formation (i.e. constant or sporadic), number non-conservation and so on. However at 850 \( \mu m \), we have a spectral energy distribution that rises as \( v^{1.5} \), leading to a strong weighting of high redshift star-formation activity in the production of the 850\( \mu m \) background of, in this simple case, \((1+z)^{3.5}\)!

Our data suggests that the median redshift for the production of the “top” 25\% of the background is around \( z = 2 \) (see Fig 7). If it is assumed that the redshift distribution of fainter sources follows that at \( S_{850} > 3 \) mJy (a plausible – but not watertight – assumption given the insensitivity of the 850 \( \mu m \) flux densities with redshift for a given class of galaxy – Fig 2) then this suggests that the bulk of star-formation in the Universe occurred at redshifts \( z << 2 \). This is illustrated in Fig 7, where the redshift distribution of the background light has been computed for a number of different star-formation histories, assuming that the energy of the star-formation emerges with the spectral energy distribution of an obscured star-burst. The distribution of observed light at \( S_{850} > 3 \) mJy in our sample is also shown (the unidentified sources have been omitted – their redshifts are unconstrained, but it is assumed that they have \( z > 2.5 \)).

Extreme galaxy formation/evolution scenarios in which 50\% of all star-formation in the Universe occurred by \( z = 3 \) would predict that 85\% of the 850 \( \mu m \) background should be produced at \( z > 3 \). Such a scenario would represent a picture in which all spheroidal stars formed very early in the Universe. With the important caveat that 850 \( \mu m \) light emitted at very high redshifts may be lurking at \( S_{850} < 3 \) mJy (this is not implausible for cosmologies with \( q_0 << 0.5 \) - see Fig 2), this prediction already appears to be inconsistent with the redshift distribution of the present \( \Delta S_{850} > 3 \) mJy sample.

On the other hand, it is clear that the sub-mm sources are much more luminous than their optical counterparts. In the ultraviolet-selected luminosity function at \( z = 3 \) constructed by Dickinson et al (1998), 22\% of the light comes from objects with luminosities of greater than \( 0.8 \times 10^{11} \ h_{50}^{-2} \ L_\odot \) (computed for \( \Omega = 1 \) and computed as \( v_{\nu} \) at 1200 \( \AA \)), equivalent to a star-formation rate of about \( 10 \ h_{50}^{-2} \ M_\odot \) yr\(^{-1}\), depending on the i.m.f.. These optical sources have a comoving number density of about \( 3 \times 10^4 \ h_{50}^{-1} \ \text{Mpc}^{-3} \) and produce an integrated luminosity density of around \( 4 \times 10^7 \ h_\odot \ L_\odot \ \text{Mpc}^{-3} \). In contrast, the sources detected in the sub-mm, producing 22\% of the FIR background at \( 2 < z < 3 \), have bolometric luminosities greater than \( 3 \times 10^{12} \ h_{50}^{-2} \ L_\odot \) (star-formation rates of 300 \( h_{50}^{-2} \ M_\odot \) yr\(^{-1}\)), number densities of \( 3 \times 10^5 \ h_{50}^{-3} \ \text{Mpc}^{-3} \) and produce an integrated luminosity density of \( 10^8 \ h_{50} \ M_\odot \ \text{Mpc}^{-3} \).

Thus, while the total production of stars is comparable (perhaps a factor of 2 higher in the sub-mm, but with some uncertainty) the sub-mm sources are much rarer but much more luminous than the optically selected sources.

The identification of a population of galaxies at high redshift that are producing a substantial fraction of present day stars in high luminosity systems is important because it is then attractive to identify these as producing the spheroidal components of galaxies. Of course, local ultra-luminous IR galaxies have long been proposed as being triggered by major mergers and resulting in the production of massive spheroids (see Sanders & Mirabel 1997 and references therein). What is new is that the population revealed in the sub-mm surveys at high redshift has a sufficiently high number density that they must be responsible for producing a significant fraction of all stars that have been formed in the Universe. These high luminosity sub-mm galaxies (with luminosities of \( 3 \times 10^{12} \ h_{50}^{-2} \ L_\odot \)) are responsible for producing 25\% of the FIR background, which itself is of order 50\% of the total extragalactic background, so these sources are presumably responsible for the generation of order 1/8 of all stars produced in the Universe.

4. Some implications for NGST

There are several implications in these developments for the design of NGST.

First, NGST will play a key role in understanding the nature of the optically fainter sources. Because of the obvious presence of large amounts of dust obscuration in these galaxies, a premium will be placed on the use of diagnostic spectral features at long wavelengths, such as H\( \alpha \) and features beyond 1 \( \mu m \), including Pa\( \alpha \). For instance the Pa\( \alpha /H\beta \) ratio provides a more robust estimate of extinction than the commonly used H\( \alpha /H\beta \) ratio. For objects at \( z > 4 \), the \( \lambda > 1 \ \mu m \) spectral range is redshifted beyond 5 \( \mu m \).
Second, although the next generation of millimetre interferometers such as the MMA/LSA should be more sensitive than SCUBA (depending on their wavelength range and how far they penetrate into the sub-mm), the most sensitive direct indicator of the presence of significant amounts of thermal dust emission at $z \sim 2$ is potentially the NGST operating in the 30 $\mu$m waveband. In other words, as the standard dust emission component is made progressively fainter, it is still visible above NGST’s projected observational detection limits at 30 $\mu$m after it has become undetectable with the MMA/LSA at $\lambda \sim 1$ mm.

5. Summary

Deep surveys in the 450 and 850 $\mu$m wavebands with the SCUBA array bolometer on the JCMT are revealing the redshifts and natures of the sources responsible for producing the far-IR/sub-mm background recently detected by COBE. Down to 3 mJy, about 25% of the background is resolved into individual sources with surface density ~ 2000 deg$^{-2}$. The number of sources is well in excess of "no-evolution" predictions and the global energetics of the optical and far-IR backgrounds suggest that around 50% of all star-formation is hidden by dust. These sources span a wide range of redshift from $z = 0.1$ to likely well in excess of $z = 3$. The redshift distribution inferred from VIK colours does not, at this stage, indicate strong departures from the shape of the star-formation history inferred from the optical/uv samples. However, while the total volume production rate of stars in the sub-mm and optical populations is comparable, the luminosities ($3 \times 10^{12} L_\odot$) of the sub-mm sources are an order of magnitude higher, and the comoving densities an order of magnitude lower, than the equivalent sources in optically selected samples. These sources, producing at least 10% of all stars in the Universe with star-formation rates of order $300 \, M_\odot$ yr$^{-1}$, are plausibly identified with galaxies forming the bulk of their metal-rich spheroidal component stars.

6. Bibliography

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Figure Captions

Fig 1: Comparison of the energy content of the visible and far-IR/sub-mm backgrounds. The former is obtained by integrating the galaxy counts in various filters, the latter is an integrated measurement from FIRAS (solid curve) and DIRBE (points with error bars). The rough equality between these backgrounds shows that the optical view of the high redshift Universe is missing about 50% of the stellar energy radiated over cosmic time.

Fig 2: Flux density vs. redshift for a luminous highly obscured starburst galaxy. The approximate detection limit of SCUBA is shown. Especially for $\Omega = 1$, the flux density is constant between 0.5 $< z <$ 6.

Fig 3: VIK colours of 6 of 7 sub-millimetre source secure identifications compared with colours of template galaxies derived from Coleman et al (1980). Typical reddening vector is shown. A third (4 of 11) sources are at $z < 1$.

Fig 4: I-band magnitudes vs. redshift (measured or estimated) for the 7 identified sources and limits to the sources for which no secure identification was made, compared with an unevolving Sbc galaxy with present-day L* luminosity. The sub-mm galaxies are generally luminous L* galaxies at visible wavelengths.

Fig 5: HST images of the 7 (of 11) securely identified sources in our sub-mm survey. These range from a $z = 0.08$ spiral (left) to two $I_{AB} \sim 24.5$ galaxies (right) that likely have $z \gtrsim 2$. The morphologies generally show signs of merger activity including prominent tails and multiple nuclei.

Fig 6: Redshift distributions suggested for our sample and for the HDF sample of Hughes et al 1998: Hatched boxes in the former represent spectroscopically confirmed secure identifications. One third of the CFRS-based sample is at $z < 1$.

Fig 7: Production of the 850 $\mu$m background from different star formation histories: The left hand panel shows different heuristic star-formation histories, ranging from "Madau" type curves peaking at $z = 1.2$ and 2, a model that rises to $z = 2$ and then has constant star-formation, a model that produces half the stars prior to $z = 3$ and finally a model with constant SFR at all epochs. For each model, the cumulative production of stars is shown in the center panel, and the cumulative distribution of light in the 850 mm background is shown in the right-hand panel. Because of the highly beneficial k-corrections at 850 $\mu$m, the light in the background is heavily weighted in favour of high redshift star-formation.