Deep sub-mm surveys: High redshift ULIRGs and the formation of the metal-rich spheroids

By SIMON J. LILLY\(^1\), STEPHEN A. EALES\(^2\), WALTER K. GEAR\(^3\), TRACY M. WEBB\(^1\), J. RICHARD BOND\(^4\), LORETTA DUNNE\(^2\)

\(^1\)Department of Astronomy, University of Toronto, 60 St. George Street, Toronto, Ontario M5S 3H8, Canada
\(^2\)Department of Physics and Astronomy, Cardiff University, P.O. Box 913, Cardiff CF2 3YB, United Kingdom
\(^3\)Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, United Kingdom
\(^4\)Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, Ontario M5S 3H8, Canada

Deep surveys of the sky at millimeter wavelengths have revealed a population of ultra-luminous infrared galaxies (ULIRGs) at high redshifts. These appear similar to local objects of similar luminosities (such as Arp220) but are much more “important” at high redshift than at low redshift, in the sense that they represent a much larger fraction of the total luminous output of the distant Universe than they do locally. In fact the ULIRGs at high redshift are producing a significant fraction (≥ 15%) of the total luminous output of the Universe averaged over all wavelengths and all epochs. The high \(z\) ULIRGs could plausibly be responsible for producing the metal-rich spheroidal components of galaxies, including the bulges that are the subject of this conference. In this case we would infer from the redshift distribution of the sources that much of this activity is probably happening relatively recently at \(z \leq 2\).

1. Introduction

Despite a great deal of progress in recent years, there still remain major uncertainties in our observational picture of the formation and evolution of galaxies in the high redshift Universe. Not least, the relationship between the star-formation activity seen at high redshift and the present-day morphological components of the galaxy population, including the bulges that are the subject of this conference, remains unclear. The origin of the stars in the metal-rich spheroidal components of present-day galaxies, which constitute a half to two-thirds of all stars in the Universe (see Fukugita et al 1998), is thus an unsolved observational question. The formation of the bulk of metal-rich spheroid stars in highly dissipational mergers of gas-rich systems at high redshifts is an attractive scenario, except for the absence (hitherto) of a substantial population of luminous star-forming galaxies at high redshifts with the high star formation rates (several \(10^2 - 10^3\) M\(_\odot\) yr\(^{-1}\)) that would be required to produce substantial spheroidal components of galaxies on typical dynamical timescales of \(10^8\) yr.

Several papers at this conference have highlighted the evidence in the present-day Universe that the spheroidal populations probably formed within the first 1/3 of the history of the Universe, i.e. at \(z \geq 1\). Certainly, the evolution seen in the optically-selected galaxy population out to \(z \sim 1\) appears to be primarily due to relatively small galaxies with irregular morphologies and to the disk components of larger galaxies (see e.g. Brinchmann et al 1998 and Lilly et al 1998a, also Guzman et al 1997, Mallen-Ornelas et al, in preparation, and references therein) and it is thus likely that the spheroids were
to a large degree in place by $z \sim 1$. The nature of the ultraviolet-selected “Lyman-break”
galaxies seen at $z > 3$ (Steidel et al 1996) and their relationship to present-day galaxies
is still quite uncertain (see e.g. Dickinson 1999, Trager et al 1997 and references therein),
and very little is really known about the nature of galaxies in the crucial intermediate
redshift range $1.5 < z < 3$.

However, it is very clear that the observational picture of the high redshift Universe
that has been gained from optical and near-infrared observations must be seriously in-
complete. The $\nu I_\nu$ energy content of far-IR/sub-mm background detected by the FIRAS
and DIRBE instruments on COBE (Puget et al 1996, Hauser et al 1998, Fixsen et al
1998) is at least as large (see e.g. Dwek et al 1998) as that of the optical/near-IR back-
ground that is obtained by integrating the galaxy number counts (e.g. Pozzetti et al 1998).
While some of the far-IR background may result from AGN activity, it is likely
that of order a half of the energy from stellar nucleosynthesis at cosmological redshifts
emerges as re-processed radiation in the far-IR. Indeed, in terms of the energy from recent
star-formation activity, the balance may be tipped even further in favour of the far-IR
because we know that a significant fraction of the optical background will be coming
from old stars - the energy of the optical/near-IR background is already three times
higher at K than at U, see Pozzetti et al (1998).

Determining the nature and redshifts of the sources responsible for the far-IR/sub-mm
background is therefore vital to our understanding of galaxy evolution. Several groups
(e.g. Small et al 1997, 1998, Hughes et al 1998, Barger et al 1998 and ourselves) are
pursuing deep surveys in the sub-millimetre waveband at 850 $\mu$m with the new SCUBA
bolometer array (Holland et al 1998, Gear et al in preparation) on the 15m James Clerk
Maxwell Telescope (JCMT) located on Mauna Kea. Working at 850 $\mu$m has a number
of rather interesting features since it is well beyond the peak of the far-IR background
(100–200$\mu$m). Not least, the $k$-corrections at 850 $\mu$m are extremely beneficial as the rest-
wave-length moves up with redshift towards the peak of thermal dust emission around 100
$\mu$m. In consequence, a typical star-burst galaxy (i.e. with an effective dust temperature
of around 30K and effective emissivity $\propto \nu^{1.5}$) has a roughly constant observed flux
density at 850 $\mu$m over the entire $0.5 < z < 5$ redshift range, especially if $\Omega = 1$ (see
Fig 3 of Lilly et al 1999) and observations at 850 $\mu$m are thus as sensitive to obscured
star-formation at very high redshifts, $z \sim 5$ as they are at $z \sim 0.5$! This remarkable
fact has a number of interesting consequences. First, “flux-density limited” samples will
approximate “luminosity limited” (or “volume limited”) samples; secondly, the redshift
distribution is likely to be only a weak function of flux density; thirdly, the knowledge
of precise redshifts is not critical for determining bolometric luminosities; and finally,
one finds that the intuition of optical observers towards quantities such as the redshift
distribution sometimes requires modification!

In this paper, we review what is currently known about the sources responsible for the
850 $\mu$m background. We take $H_0 = 50h_{50}$ kms$^{-1}$Mpc$^{-1}$ and for simplicity generally
assume a matter-dominated $\Omega = 1$ cosmology.

2. Resolving the sub-mm background into discrete sources

In the last six months, four independent groups have published first results from deep
surveys at 850 $\mu$m. Small et al (1997,1998) have undertaken an ingenious survey using the
gravitational lensing effect of moderate redshift clusters of galaxies to amplify background
sub-mm sources and now have a sample of 17 sources at $S_{850} > 6$ mJy (3$\sigma$). The
remaining surveys have been “field” surveys. Hughes et al (1998) published a single very
deep image of the HDF that revealed 5 sources at $S_{850} > 2$ mJy (4$\sigma$), Barger et al (1998)
had 2 sources at $S_{850} > 3$ mJy (3σ) and our own program (Eales et al 1999) has 12 published sources published with $S_{850} > 3$ mJy (3σ) with another 20 or so sources at various stages of identification and analysis - the properties of these appear consistent with the first 12, but will not be discussed here.

Given the small numbers involved, the number counts of sources from these surveys are consistent (see Fig 1 - adapted from Blain et al 1998b) and indicate substantial excesses over the number of sources predicted in “no-evolution” replications of the local IRAS 60 mm luminosity function (see Smail et al 1997, Eales et al 1999). The direct counts at $S_{850} > 2$ mJy have been extended to about 1 mJy with a $P(D)$ analysis in the HDF (Hughes et al 1998) and by a lens inversion analysis by Smail et al (1999).

While many of the sources have been detected at low S/N ratios, the chopping and nodding employed in sub-mm observations lend themselves to a number of straightforward statistical tests (e.g. searching for negative images at the same level of significance) and the great majority of the claimed sources are probably real. It should be noted that all of the blank-field surveys are approaching or have reached the confusion limit. For instance, at the $S_{850} \sim 3$ mJy 3σ limit of our own survey there are already about 40 beams per source, the conventional point at which confusion effects become significant.
The upper panel in Fig 1 shows the cumulative fraction of the 850 μm background (taken to be 12 mJy arcmin$^{-2}$, Fixsen et al 1998) that is produced by these detected sources. It should be noted that already by 3 mJy we are accounting for 20% of the background, a fraction that increases to 50% at the faintest limit, $S_{850} \sim 1$ mJy, probed by the statistical studies.

3. Identifications of the sub-mm sources

3.1. How reliable are the identifications

The SCUBA beam at 850 μm is 15 arcsec FWHM, necessitating a probabilistic approach to identifications on deep optical or near-infrared images. Some of the sub-mm sources are μJy radio sources enabling more accurate, arcsec-level, positions to be determined and these can be identified relatively unambiguously. The fraction of sources that are detectable as faint radio sources is not well determined at this point. In the HDF, Richards (1999) claimed 3 of 5 of the Hughes et al sub-mm sources were detected at $S_{850 GHz} > 10$ mJy (although this required a quite large and controversial offset of 6 arcsec with respect to the Hughes et al (1998) sub-mm astrometric reference frame). In our own CFRS-14 sample, for which the radio catalogue extends to $S_{5GHz} \sim 16$ mJy (Fomalont et al 1992) we find about 33% of sub-mm sources to be radio sources (and also, since they have similar surface densities, a similar fraction of radio sources to be sub-mm sources). In the future, millimetre wavelength interferometry may produce better positions for the remainder.

All of the survey programs have searched for identifications with extragalactic objects. It is possible to compute the probability that the nearest member of a population of candidate identifications (i.e. optical galaxies) with surface density $n$ is located within a distance $d$ from a random position on the sky, $P = e^{-\pi nd^2}$ (e.g. Downes et al 1986) and this $P$ statistic has been used by many workers in the identification of sub-mm sources (e.g. Hughes et al 1998, Smail et al 1998). There is already a subtlety in the use of $P$, in that if the density of sources $n$ used is based on the magnitude of the candidate identifications, i.e. $n(< m)$, then $P$ will suffer an a posteriori bias, but this can be (and has been) dealt with either analytically or through Monte Carlo simulations. The $P$ statistic represents a starting point, but is not what is really required, which is rather the probability that a particular claimed identification is, in fact, correct. The quantity $P$ tells us the fraction of sources in a sample of size $N$ that would be expected to have an incorrect candidate identification lying within this distance $d$, i.e. $N_{spurious}(< P) = NP$. Thus, a low value of $P$ for any individual source is not, on its own, enough to make an identification secure. Rather, one has to look at the sample as a whole and determine the number of identifications in the sample (with a certain value of $P$) relative to the number of spurious identifications (with that same $P$) that would have been expected if the two populations were completely unrelated. Only if this ratio is high can a particular individual source with that value of $P$ be regarded as securely identified. This is illustrated in Fig 2, which shows the distribution of (corrected) $P$ values for the identifications in the three main published programs (the solid histograms) compared with the distribution of $P$ expected if the optical and sub-mm populations were completely unrelated (the smooth line). Statistically, sources lying “below” the smooth line cannot therefore be regarded as identified, regardless of their value of $P$, since that number of objects would have been expected by chance!

Our conclusion from Fig. 2 is that in all of the deep sub-mm samples studied to date we have reliable identifications for only about half (40-60%) of the sub-mm sources,
Figure 2. The distribution of $P$ values in the three main published surveys (solid histograms - upper two panels Hughes et al (1998) based on magnitudes and redshifts, then our own sample and the Smail et al (1998) lensing sample). The best measure of whether individual identifications are correct is given by comparing the number of identifications in the whole sample with a particular value of $P$ with the number, $N_P$, that would have been expected by chance (solid line). This suggests that about 50% of the sources in all the samples are have been correctly identified.

regardless of whether identifications for the remainder have been claimed or not. This is a handicap, but as we will see below, it is not as serious as one might suppose. Furthermore, the statistics of the identifications already enable us to make an important statement: At least half (and quite possibly all) of the high latitude 850 $\mu$m sources must be extragalactic in nature.

3.2. The redshift distribution of the identifications
Hughes et al in their HDF sample emphasized the high redshifts of their identifications. In our own program (Lilly et al 1998, 1999), we found that many of the sub-mm identifications had already been catalogued in the CFRS program and that in fact three of the first 12 sources had spectroscopic redshift measurements at $z < 1$ (at $z = 0.074$, $0.55$ and $0.66$). For the remainder, we have estimated redshifts on the basis of the optical-infrared $U\text{VI}K$ colours. We concluded that all the initial eight identifications (of which at least six may be regarded as secure) were optically luminous galaxies (comparable to present-day $L*$) spanning a broad range of redshifts $0.08 < z < 3$, with four at $z < 1$. The upper limit at $z \sim 3$ comes from detections in the $U$-band. With the present rather
limited data, the observed properties of the four unidentified empty field sources in our sample would be broadly consistent with those of the identified galaxies if they were placed anywhere over a rather wide range of redshifts, $2 < z < 10$. Redshifts as low as $z \sim 1$ however would not be excluded by the present data but would require a higher extinction, as in VII Zw031 (see Trentham et al. 1999) A reasonable guess for the median redshift is $< z > \sim 2$.

As discussed in Lilly et al. (1999 - see their Fig 10ab), these results appear to be broadly similar to those of the other surveys, especially if the Richards (1999) modification of the HDF identifications are adopted. The lensed sample of Smail et al (1998) does not at present have redshift estimates (except for constraints based on detection in $B$ or $V$) but appears to have a similar distribution in $I_{AB}$ magnitude especially when an average lens amplification of a factor of 2.5 is taken into account.

3.3. The nature of the sub-mm sources

As noted above, any source detected at $S_{850} \geq 3$ mJy that lies at $z > 0.5$ must have a luminosity above that of Arp 220, i.e. $L \geq 3 \times 10^{12}h_{50}^{-2}L_{\odot}$. Assuming the energy comes from star-formation as opposed to black-hole accretion, this luminosity corresponds to a substantial star-formation rate of $\geq 600h_{50}^{-2}M_{\odot}$ yr$^{-1}$.

The broad-band spectral energy distributions of the identifications in our own sample, as defined from the optical through the far-IR component to the radio, from measurements or limits at 0.8 $\mu$m, 15 $\mu$m, 450 $\mu$m, 850 $\mu$m and at 5 GHz, are consistent with the measured/estimated redshifts of the identifications and a rest-frame SED that broadly matches that of Arp 220.

The galaxies have a range of optical colours, but are on average a little redder in $(V - I)$ than typical field galaxies, consistent with what is known about the ultraviolet properties of local ULIRGs (Trentham et al. 1999). The $(V - I), I$

for our identifications and for those in the Smail et al program match nicely the expectations based on local ULIRGs (Trentham et al. 1999). The HST morphologies of the $z > 0.5$ identifications in our sample range from relatively normal looking galaxies to clear examples of mergers, but nearly all show some sign of peculiarity in the form of secondary nuclei or asymmetrical outer isophotes. Little is known about the ultraviolet morphologies of ULIRGs at low redshift, but the Trentham et al (1999) study shows considerable diversity and substantial differences from the optical morphologies.

In summary, in essentially all respects that can presently be studied, the $z > 0.5$ sources in our sample appear to be very similar to local ULIRG prototypes such as Arp 220.

4. The significance of ULIRGs at high redshift

The results outlined above lead robustly to a very important conclusion: ULIRGs as a class are a much more important component of the galaxy population (in that they produce a much higher fraction of the total luminous output) at high redshift than at low redshift. In the local Universe, ULIRGs of luminosities greater or equal to that of Arp 220 (i.e. $2 \times 10^{12}h_{50}^{-2}L_{\odot}$) contribute only about 1% of the far-IR luminous output of the galaxy population (Soifer et al. 1987, Saunders et al. 1990, Sanders and Mirabel 1996). In contrast, at high redshifts ($z > 1$), similar objects must produce at least 30% of the far-IR/sub-mm background (for $\Omega = 1$, more for low $\Omega$ since Arp 220 would lie further down the $N(S)$ distribution), which we have seen is at least equal in energy content to the optical/near-IR background. Thus, high luminosity obscured objects are much more common, relatively, at high redshift, and are in fact producing a substantial fraction
Figure 3. Estimate of the cumulative bolometric luminosity function of the sub-mm population from our own sample (points), the local IRAS 60µm population, and the $z \sim 3$ ultraviolet-selected “Lyman-break” population (uncorrected for extinction). The $1 < z < 3$ sub-mm points show minimum and maximum values according to whether the four “empty field” sources are at $z > 3$ or $1 < z < 3$. Likewise, the $3 < z < 8$ point assumes that the “empty fields” are at $z > 3$.

(15%) of the total luminous output of the Universe averaged over all epochs and all wavebands.

The cumulative bolometric luminosity function in the far-IR derived from our own sample is shown in Fig 3 compared with the local IRAS luminosity function and the ultraviolet luminosity function for the Lyman-break galaxies constructed by Dickinson (1999).

5. Interpretation of the redshift distributions

The relatively small number of sources (no more than 50% of the sample) that can possibly be at very high redshifts ($z > 3$) already sets quite strong constraints on the amount of high luminosity obscured star-formation that can take place at these redshifts. This is because, as pointed out in previous papers (Lilly et al 1998, 1999), the beneficial $k$-corrections produce a strong weighting of high redshift star-formation activity in the production (in redshift space) of the 850 µm background relative to the production of stars (in redshift space). This weighting is simply $f_\nu(\nu_{em})/f_\nu(\nu_{obs})$, or $(1 + z)^{3.5}$ over much of the redshift range of interest $0 < z < 6$. In Fig 4 (from Lilly et al 1999), we
Figure 4. Production of the 850 µm background from different star formation histories: The left hand panel shows five different heuristic star-formation histories. For each model, the cumulative production of stars is shown in the center panel, and the cumulative distribution of light in the 850 µm background is shown in the right-hand panel. Because of the highly beneficial $k$-corrections at 850 µm, the light in the background is heavily weighted in favour of high redshift star-formation. Models in which half the obscured star-formation in the Universe occurred prior to $z \sim 3$ predict that only 15% of the sources with $S_{850} < 3$ mJy have $z > 3$ - a highly unlikely situation. The irregular line in the left-most panel shows the distribution in redshift of the background produced by the observed sources - illustrating the effect of assuming that the sources below the limit of the survey in fact have the same redshift distribution. This would require a falling luminosity density at high redshifts would imply that most stars formed in these obscured objects did so at $z \leq 2$.

have computed the redshift distribution of the 850 µm background light for a number of different star-formation histories, assuming that the energy of this star-formation emerges with the spectral energy distribution of an obscured star-burst, like Arp 220. It can be seen that galaxy formation/evolution scenarios in which 50% of all dust enshrouded star-formation in the Universe occurred prior to $z = 3$ predict that 85% of the 850 µm background had been produced at $z > 3$. The distribution of observed light at $S_{850} > 2.8$ mJy in our identified source sample is also shown. This does not reach unity because the unidentified sources have been omitted since their redshifts are unconstrained (but it is assumed for this purpose that they have $z > 2.5$) and the contribution from the two less securely identified galaxies estimated to lie at around $z \sim 2.5$ is shown as a dotted line.

Even if we make no assumption at all about the redshifts of the fainter sources with $S_{850} < 3$ mJy, our observations would already appear to require that at least 15% of the
850 µm background must be produced at $z < 3$, which is only barely consistent with a scenario in which 50% of obscured star-formation takes place at $z \geq 3$.

If we speculatively assume that the redshift distribution of fainter sources with $S_{850} < 3$ mJy follows that at $S_{850} > 3$ mJy (a plausible, but not watertight, assumption given the flatness of the 850 µm flux density-redshift relation, see also the models of Blain et al 1998a) then our results then suggest that the great bulk of obscured star-formation in the Universe occurred at redshifts $z < 3.0$. While this analysis can not be regarded as conclusive until we penetrate deeper in to the background, Fig 4 suggests that the cumulative production of the 850 µm background appears to follow well the expectations of models in which the luminosity density in the far-IR (at least in high luminosity obscured objects) peaks in the $1.2 < z < 2$ range and falls thereafter. Interestingly, initial indications for a decline in the ultraviolet luminosity density of the Universe at high redshifts (Madau 1996, 1997) have not been borne out by more recent work (Steidel et al 1999).

6. The relationship to the Lyman-break ultraviolet-selected galaxy population

As shown in Fig 12 of Lilly et al (1999) the bolometric output in the far-IR of the high luminosity ($L \geq 3 \times 10^{12} h_{50}^{-2} L_\odot$) high $z$ ULIRG population already matches that in the ultraviolet of the whole "Lyman-break" population of galaxies, even though the former only comprise the "top" 20% of the 850 µm background.

Estimates of the reddening of the Lyman-break galaxies based on the observed ultraviolet continuum slope suggest that for typical LBG the far-IR luminosity would be between 2 - 7 times that seen in the ultraviolet (Dickinson 1999, see also Pettini et al 1998) for SMC and Calzetti extinction curves, with higher values being claimed by Meurer et al (1997). These typical objects, with "corrected" star-formation rates of up to $30 - 100 h_{50}^{-2} M_\odot yr^{-1}$ would be undetectable with SCUBA at present, but would have to be responsible for a significant fraction of the background.

Obviously the estimation of bolometric luminosities on the basis of extinction in the ultraviolet is highly uncertain requiring an assumed extinction curve that largely reflects the geometrical distribution of stars and dust. This is especially true in the high extinction regime (see the three examples of local ULIRGs in Trentham et al 1999). Nevertheless, preliminary indications (Steidel, private communication) are that the number of very highly extinguished LBG with "corrected" Arp220-level luminosities (i.e. after correction with the Calzetti reddening curve) are roughly consistent with the number directly observed in the sub-mm surveys described here, which have $\phi \sim 10^{-4} h_{50}^2$ Mpc$^{-3}$, Fig 3). This agreement is encouraging, though possibly fortuitous given the uncertainties in the reddening correction applied to the optical sample. The sub-mm sample may also contain some ULIRGs that are so heavily obscured as to be completely absent from the present LBG samples.

7. The nature of the obscured energy sources

A difficult question concerns the fraction of the far-IR energy that comes from hidden active galactic nuclei. In the local Universe, the evidence from mid-IR emission features (Genzel et al 1998) is that AGN provide a significant but not dominant (25% - 50%) contribution to ULIRGs at these luminosities and this seems a reasonable first guess as to the situation at high redshifts. The ultraviolet spectrum of the highly luminous sub-mm source SMM02399-0136 (Ivison et al 1998) shows spectroscopic indications for
an AGN but this same source also exhibits strong, star-burst like, CO detections (Frayer et al 1998, see also Frayer et al 1999). For all but the brightest sources (which may be tackled by SIRTF) these mid-IR diagnostics may be unobservable until NGST flies - and even then only if it has a mid-IR spectroscopic capability.

Ascribing a dominant fraction of the energy output of this population to AGN would require a major upwards revision in the total energy output of AGN. On the other hand, several authors have stressed the inadequacy of the “known” quasar population to produce the required mass of black holes (integrated over the population). Using the Magorrian et al (1996) relationship between black hole mass and stellar bulge mass ($M_{BH} \sim 0.006 M_*$) in local galaxies and assuming a radiative efficiency $\epsilon \sim 0.1$ for black hole accretion and an energy release of $0.016 M_Z c^2$ for the return of $M_Z$ of metals (Songaila et al 1990) it is easy to show that the bolometric light output associated the production of the black holes and stellar metals in typical spheroids should be comparable:

$$\frac{L_{AGN}}{L_{star}} \sim \frac{\epsilon M_{BH} c^2}{0.016 M_Z c^2} \sim \frac{M_{BH}}{M_{star}} \frac{1}{0.0052} \sim 2$$

On the other hand, the approximate consistency with the extinction-corrected properties of the LBG population noted above suggests that much of the far-IR background is indeed coming from stars. Observational resolution of this important question at better than the factor of two level will be challenging.

8. The formation of spheroids?

The identification, in the sub-mm, 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 metal-rich spheroidal components of galaxies, including the bulges of present-day spiral galaxies. 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 and Mirabel 1997 and references therein). The high individual luminosities ($\geq 3 \times 10^{12} h_{50}^{-2} L_\odot$) and implied star-formation rates ($\geq 600 h_{50}^{-2} M_\odot yr^{-1}$) are consistent with making substantial stellar populations on dynamical timescales.

It should be stressed that the ULIRG population revealed in the sub-mm surveys at high redshift has a sufficiently high number density (more than 100 times higher than in the present-day Universe - Fig 3) that they could be responsible for producing a significant fraction of all stars that have been formed in the Universe, since they are responsible for producing, in the far-IR, a significant fraction of the entire bolometric extragalactic background light. In more absolute terms, a star-formation rate of $600 h_{50}^{-2} M_\odot yr^{-1}$ maintained for $4 h_{50}^{-3}$ Gyr at a number density of $\phi \sim 10^{-4} h_{50}^{3}$ Mpc$^{-3}$ would yield a stellar mass density of $2.4 \times 10^8 M_\odot$ Mpc$^{-3}$. It should be recalled (e.g. Fukugita et al 1998) that the spheroids contain a half to two-thirds of all stars in the Universe or about $0.7 - 2.0 \times 10^8 h M_\odot$ Mpc$^{-3}$. So the numbers are in the right ball-park.

The combination of the high integrated production of stars, the high star-formation rates, the incidence of merger-like morphologies and the obvious presence of substantial amounts of dust, make it attractive, though still speculative, to associate these galaxies with the production of the metal-rich spheroid component of galaxies. In this case, these first data from our survey (see Fig. 4) suggest that much of this activity, conservatively at least 50%, and probably much more, has happened at relatively recent epochs, i.e. $z < 3$. 
The research of SJL and JRB is supported by the Natural Sciences Engineering Research Council of Canada and by the Canadian Institute for Advanced Research. The Research of SAE and WKG is supported by the Particle Physics and Astronomy Research Council in the United Kingdom. The support of all of these agencies is gratefully acknowledged.

REFERENCES

Barger, A., Cowie, L., Sanders, D., Fulton, E., Taniguchi, Y., Sato, Y., Kaware, K., Okuda, H., 1998, Nature, 394, 248.

Blain, A., Longair, M., 1993, MNRAS, 264, 509.

Blain, A., Smail, I., Ivison, R., Kneib, J.-P., 1998, astro-ph/9806002.

Blain, A., Kneib, J.P., Ivison, R., Smail, I., 1998, astro-ph/9812412.

Brinchmann, J., Abraham, R., Schade, D., Tresse, L., Ellis, R., Lilly, S., Le Fvre, O., Glazebrook, K., Hammer, F., Colless, M., Crampton, D., Broadhurst, T., 1998, ApJ, 499, 112.

Connolly, A., Szalay, A., Dickinson, M., Subba Rao, M., Brunner, R., 1997, ApJ, 486, L11.

Dickinson, M., 1999, In “The Hubble Deep Field” (ed. M. Livio, M. Fall and P. Madau), p219

Downes, A.J.B., Peacock, J.A., Savage, A., carrie, D., 1986, MNRAS, 218, 31.

Dwek, E., Arendt, R., Hauser, M., Fixsen, D., Kelsall, T., Leisawitz, D., Pei, Y., Wright, E., Mather, J., Moseley, S., Odegard, N., Shafer, R., Silveberg, R., Welland, I., 1998, ApJ, 508, 106.

Eales, S., Lilly, S., Gear, W., Bond, J.R., Dunne, L., Hammer, F., Le Fvre, O., Crampton D., 1998, ApJ, in press (Paper 1)

Fixsen, D., Dwek, E., Mather, J., Bennet, C., Shafer, R., 1998, ApJ, 508, 123.

Fomalont, E., Windhorst, R., Kristian, J., Kellerman, K., 1991, AJ, 102, 1258.

Frayer, D.T., Ivison, R.J., Scoville, N.Z., Yun, M., Evans, A.S., Smail, I., Blain,A.W., Kneib, J.-P., ApJ 506, 7.

Frayer, D.T., Ivison, R.J., Scoville, N.Z., Evans, A.S., Yun, M., Smail, I., Barger, A., I., Blain,A.W., Kneib, J.-P., ApJLett 514, L13.

Genzel, R., Lutz, D., Sturm, E., Egami, E., Kunze, D., Moorwood, A.F.M., Rigopoulou, D., Spoon, H., Sternberg, A., Tacconi-Garman, L., Tacconi, L., Thatte, N., 1998, ApJ, 498, 579.

Guzman, R., Gallego, J., Koo, D., Phillips, A., Lowenthal, J., Faber, S.M., Illingworth, G., Vogt, N., 1998, ApJ, 489, 559.

Haehnelt, M.G., Natarajan, P., Rees, M.J., 1998, MNRAS, 300, 817.

Hauser, M., Arendt, R., Kelsall, T., Dwek, E., Odegard, N., Welland, J., Freundensch, H., Reach, W., Silverberg, R., Modeley, S., Pei, Y., Lubin, P., Mather, J., Shafer, R., Smoot, G., Weiss, R., Wilkinson, D., Wright, E., 1998, ApJ 508, 25.

Holland, W.S., Robson, E.I., Gear, W.K., Cuningham, C.R., Lightfoot, J.F., Jenness, T., Ivison, R., Stevens, J.A., Ade, P.A.R., Griffin, M.J., Duncan, W.D., Murphy, J.A., Naylor, D.A., 1998, MNRAS, in press, astro-ph/9809122.

Hughes, D., Serjeant, S., Dunlop, J., Rowan-Robinson, M., Blain, A., Mann, R., Ivison, R., Peacock, J., Elstathion, A., Gear, W., Oliver, S., Lawrence, A., Longair, M., Goldschmidt, P., Jenness, T., 1998, Nature 394, 241.

Ivison, R., Smail, I., Le Borgne, J-F., Blain, A., Kneib, J-P., Kerr, T., Bezecourt, J., Davie, J., 1998, MNRAS, 298, 583.

Lilly, S., Cowie, L., 1987, In “Infrared Astronomy with Arrays” (eds. Wynn-Williams, G., Becklin, E.), UH, Honolulu, p.473.

Lilly, S., Le Fvre, O., Crampton, D., Hammer, F., Tresse, L., 1995a, ApJ, 455, 50.

Lilly, S.J., Hammer, F., Le Fvre, O., Crampton, D., 1995b, ApJ, 455, 75.

Lilly, S.J., Le Fvre, O., Hammer, F., Crampton, D., 1996, ApJ, 460, L1.
Lilly, S.J., Schade, D., Ellis, R., Le Fvre, O., Brinchmann, J., Tresse, L., Abraham, R., Hammer, F., Crampton, D., Colless, M., Glazebrook, K., Mallen-Ornelas, G., Broadhurst, T., 1998a, ApJ, 500, 75.

Lilly, S.J., Eales, S.A., Gear, W., Dunne, L., Bond, J.R., Hammer, F., Le Fvre, O., Crampton, D., 1998b, In “NGST: Scientific and Technical Challenges”, Proceedings of the 34th Liege International Astrophysics Colloquium, (ed. B. Kaldeich-Schrmann), ESA.

Madau, P., Ferguson, H., Dickinson, M., Giavalisco, M., Steidel, C., Fruchter, A., 1996, MNRAS, 283, 1388.

Madau, P., Pozetti, L., Dickinson, M., 1998, ApJ, 498, 106.

Meurer, G., Heckman, T., Lehnert, M., Leitherer, C., Lowenthal, J., 1997, AJ, 114, 51.

Pettini, M., Kellogg, M., Steidel, C., Dickinson, M., Adelberger, K., Giavalisco, M., 1998, ApJ, 508, 539.

Pozzetti, L., Madau, P., Zamorani, G., Ferguson, H.C., Bruzual, G., 1998, MNRAS, 298, 1133.

Puget, J-L., Abergel, A., Bernard, J-P., Boulanger, F., Burton, W.B., Desert, F.X., Hartmann, D., 1996, A&A, 308L, 5P.

Richards, E.A., 1998, astro-ph/9811098

Sanders, D., Mirabel, I., 1996, ARA&A, 34, 749.

Saunders, W., Rowan-Robinson, M., Lawrence, A., Efstathiou, G., Kaiser, N., Ellis, R.S., Frenk, C., 1990, MNRAS, 242, 318.

Sawicki, M., Lin, H., Yee, H., 1997, AJ, 113, 1.

Smail, I., Ivison, R., Blain, A., 1997, ApJ, 490, L5.

Smail, I., Ivison, R., Blain, A., Kneib, J-P, 1998, ApJ, 507, L21.

Songaila, A., Cowie, L.L., Lilly, S.J., 1990, ApJ, 348, 371.

Steidel, C., Giavalisco, M., Pettini, M., Dickinson, M., Adelberger, K., 1996, ApJLett 462 L17.

Steidel, CV., Adelberger, K., Giavalisco, M., Dickinson, M, Pettini, M., 1998, astro-ph/9811400

Trager, S., Faber, S., Dressler, A., Oemler, A., 1997, ApJ, 485, 92

Trentham, N., Kormenday, J., Sanders, D., 1999, astro-ph/9901382
