Sub-mm clues to elliptical galaxy formation

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There is growing evidence that, at the $S_{850\mu m} < 1\,\text{mJy}$ level, the sub-mm galaxy population (and hence a potentially significant fraction of the sub-mm background) is associated with the star-forming Lyman-break population already detected at optical wavelengths. However, the implied star-formation rates in such objects (typically $3 - 30\,M_\odot\,\text{yr}^{-1}$) fall one or two orders of magnitude short of the level of star-forming activity required to produce the most massive elliptical galaxies on a timescale $\sim 1\,\text{Gyr}$. If a significant fraction of massive ellipticals did form the bulk of their stars in short-lived massive starbursts at high redshift, then they should presumably be found among the brighter, $S_{850\mu m} \simeq 10\,\text{mJy}$ sub-mm sources which are undoubtedly not part of the Lyman-break population. A first powerful clue that this is indeed the case comes from our major SCUBA survey of radio galaxies, which indicates that massive dust-enshrouded star-formation in at least this subset of massive ellipticals is largely confined to $z > 2.5$, with a mean redshift $z \simeq 3.5$. While radio selection always raises concerns about bias, I argue that our current knowledge of the brightest ($S_{850\mu m} \simeq 10\,\text{mJy}$) sub-mm sources detected in unbiased SCUBA imaging surveys indicates that they are also largely confined to this same high-$z$ regime. Consequently, while the most recent number counts imply such extreme sources can contribute only 5-10% of the sub-mm background, their comoving number density (in the redshift band $3 < z < 5$) is $\simeq 1 - 2 \times 10^{-5}\,\text{Mpc}^{-3}$, sufficient to account for the formation of all ellipticals of comparable mass to radio galaxies ($\geq 4L^*$) in the present-day universe.

1 Introduction

The formation mechanism of elliptical galaxies remains a fundamental and controversial issue in cosmology. In current models of galaxy formation dominated by cold dark matter (CDM), elliptical galaxies arise from the merging at low redshift of intermediate-mass discs, and some recent data have been interpreted as supportive of the implied gradual formation of massive ellipticals at relatively low redshift. However, the validity of these analyses has recently been questioned, and other observational evidence at low/moderate redshift, continues to favour a picture in which at least some massive ellipticals formed the bulk of their stars in a relatively short-lived ($\lesssim 1\,\text{Gyr}$) massive starburst at high redshift ($z > 3$). While this high-redshift star-formation scenario might only apply to a subset of ellipticals, it can be argued that it applies to massive ellipticals in general. Moreover, the clarification of the link between black-hole and spheroid mass suggests that the hosts of AGN may be more representative of spheroids in general than previously supposed.
1. Observing spheroid formation - optical versus submm

It has been argued that the formation of present-day galactic bulges/spheroids has already been observed at optical wavelengths, through the discovery of the Lyman-break population at $z \approx 2 - 4$. However, even if substantial corrections are made to correct for the effects of dust, the inferred star-formation rates in these objects are relatively modest (typically $3 - 30 M_{\odot} \text{yr}^{-1}$). Even luminous Lyman-break objects thus appear to fall over an order of magnitude short of the high star-formation rates ($\approx 1000 M_{\odot} \text{yr}^{-1}$) required to construct the stellar populations of the most massive ellipticals on a timescale $\leq 1 \text{Gyr}$.

Direct confirmation of this comes not only from the difficulty experienced in detecting individual, unlensed Lyman-break objects with SCUBA, but also from the achievement of a statistical detection of the bright end of the Lyman-break population in the deep SCUBA image of the HDF. The basic evidence for this result is shown in Fig.1; Lyman-break galaxies with raw (uncorrected, UV-derived) star-formation rates $\approx 1 h^{-2} M_{\odot} \text{yr}^{-1}$ are detected, statistically, in the SCUBA image at flux densities of $S_{850 \mu m} \approx 0.2 \text{ mJy}$. This number implies that the ratio of hidden-to-visible star-formation in these objects is $5 \pm 1.5$ (consistent both with dust-screen models and with models which assume the first ‘15 Myrs-worth’ of star-formation in giant molecular clouds is always essentially invisible at UV wavelengths). It also implies that the Lyman-break population is probably responsible for a significant, albeit highly-uncertain fraction of the sub-mm background ($\sim 25\%$).
This independent check on the hidden:visible star-formation ratio in Lyman-break galaxies confirms that optical surveys very rarely uncover galaxies forming stars at the level of $100 - 1000 M_\odot \, yr^{-1}$. One possible explanation for this is that the formation of the stellar populations of massive ellipticals is too widely distributed in space and/or time to be identified with a very violent event. Observationally, however, it remains possible that such massive starbursts are prevalent at high redshift, but are either too dust-enshrouded, or at too extreme $z$ to be detected in existing optical-UV drop-out surveys.

In fact, since the first sub-mm detections of the $z \simeq 4$ radio galaxies 4C41.17 and 8C1435+635 five years ago, it has been clear that such massive dust-enshrouded high-$z$ starbursts do at least exist. These galaxies display exactly the properties expected of a young massive elliptical, with inferred dust-enshrouded star-formation rates $\simeq 1000 M_\odot \, yr^{-1}$. However, the relevance of such extreme sources to the general elliptical population has been unclear.

3 Sub-mm studies of radio galaxies out to $z \simeq 4$

3.1 SCUBA photometry of radio galaxies

These pioneering sub-mm observations have therefore raised the important issue of whether all luminous sub-mm sources are largely confined to extreme redshift ($z \simeq 3 - 5$). A powerful clue that this may be true comes from our major SCUBA study of radio galaxies spanning the redshift range $0 < z < 5$. Such a survey is potentially biased, being based on an (arguably) special subset of massive ellipticals. However, it does offer the advantages of ready-made redshift information and accurately known positions (allowing SCUBA to be used in its most sensitive photometry mode). These advantages have enabled us to deduce that the typical level of dust-enshrouded star-formation in radio galaxies grows rapidly beyond $z \simeq 2$, continuing to rise out to $z \simeq 4$ (Fig.2).

How biased might this result be? Interestingly the median redshift of the sub-mm detections in the radio-galaxy sample is $z \simeq 3$, consistent with that derived for the (cluster-lensed) field population. However, as shown in Fig.2, the average sub-mm luminosity continues to rise beyond $z \simeq 3$. This is because 4 of the 5 most luminous sub-mm sources ($S_{500\mu m} > 5$ mJy) in the sample lie at $z > 3$. Could this be true for luminous sub-mm sources in general?

3.2 SCUBA imaging of radio galaxies

Already it is clear that large sub-mm luminosities at $z \simeq 3 - 4$ are not simply confined to the host galaxies of AGN. New, deep, SCUBA imaging of the regions around several of the above-mentioned radio galaxies has revealed even
Figure 2: The rapid growth of average sub-millimetre luminosity with increasing redshift found for powerful radio galaxies spanning the redshift range $0.5 < z < 4.5$. The datapoints are the result of SCUBA observations of a sample of $\approx 50$ radio galaxies, placed in redshift bins of unit width. The curve has the form $L \propto (1+z)^4$, and serves to illustrate the dramatic nature of the increase in characteristic sub-mm luminosity, particularly beyond $z \approx 2.5$. This result suggests that the epoch of maximum star-formation in the massive elliptical hosts of radio sources lies at $z \approx 3 - 4$.

more sub-mm-luminous companion sources, at the same redshift. The implication is that high-$z$ radio galaxies act as signposts towards young clusters in which much of the eventual stellar content of the cluster ellipticals is forming in massive dust-enshrouded starbursts ($\approx 1000M_\odot yr^{-1}$). This is consistent with the apparent age and coevality of present-day cluster ellipticals. Moreover, the faintness of the possible optical IDs of these very luminous sub-mm sources indicates that this process is basically invisible at optical wavelengths.

4 Bright sources from unbiassed sub-mm surveys

With the advent of sensitive sub-mm imaging with SCUBA, unbiassed sub-mm surveys with the potential to properly quantify the prevalence of massive dust-enshrouded starbursts at high $z$ can now be carried out. Several such surveys are underway, but it is clear that reliable source detection, optical/IR identification, and redshift determination is still in its infancy.

One of the main reasons for this somewhat slow progress is the fact that it is only for bright ($S_{850\mu m} > 8$ mJy) SCUBA sources that unconfused positions can be reliably obtained with, for example, follow-up mm interferometry. This is well demonstrated by the effort required to determine an accurate position for the brightest source (HDF850.1; $S_{850\mu m} = 7$ mJy) from our SCUBA survey of the HDF. Indeed, even with sub-arcsec positional accuracy, it can prove
Figure 3: Observed 450/850\(\mu\)m and 850/1350\(\mu\)m flux-density ratios for HDF850.1 compared with what might be expected as a function of redshift. The curves show the extreme range of colours for SEDs that represent dust enshrouded starburst galaxies and AGN - Arp220 (solid), M82 (dashed) and Mkn231 (dot-dashed). The solid horizontal line in the left-hand panel shows the existing upper limit to the 450/850\(\mu\)m flux ratio for HDF850.1. The horizontal lines in the RH panel show the measured 850/1350\(\mu\)m flux ratio for HDF850.1 (solid line), and the \(\pm 1\sigma\) errors on this ratio (dot-dashed lines).

4.1 The 8-mJy SCUBA survey

In an effort to assemble a substantial and unbiased sample of sub-mm sources of a luminosity comparable to or greater than HDF850.1, we are currently undertaking an ‘8-mJy’ SCUBA survey covering 400 sq.arcmin. In comparison to existing SCUBA surveys this new survey has four key advantages. First, its flux limit is sufficiently bright to allow follow-up with existing instrumentation (e.g. the IRAM PdB interferometer) which should ultimately yield an accurate (\(~1\) arcsec) position for every source. Second, there is no a priori reason to expect the sources to be lensed. Third, the flux limit is sufficiently bright that sub-mm confusion is not a problem. Fourth, and scientifically most important, any sources discovered in this survey must be as bright or brighter in the
sub-mm than the extreme radio galaxies mentioned above. This survey is therefore optimised for the detection of starbursts with SFR $\approx 1000 \text{M}_{\odot} \text{yr}^{-1}$. Initial results from this survey indicate a cumulative source count of 250$^{\pm}70$ degree$^{-2}$ at flux densities $S_{850\mu m} \geq 10\text{mJy}$, and provide preliminary evidence that these luminous sub-mm sources are strongly clustered (Fig.4).

The crucial next stage is to determine the nature/redshift of the bright SCUBA sources in this survey. As a first step we have been investigating the two brightest sources detected to date in our 8-mJy survey. These two sources - ELAIS850.1 and Lockman850.1 - have flux densities at 850$\mu m$ of 15 and 11 mJy respectively, making them among the very brightest unlensed SCUBA sources discovered from blank-field surveys so far. For Lockman850.1 we have obtained a clear detection at 1.3mm with the IRAM PdB interferometer, yielding its position to sub-arcsec accuracy, and similar observations are also planned for ELAIS850.1. We have also obtained deep K-band images of these sources with UFTI on UKIRT. The results of this sub-mm/mm/infrared/optical comparison are shown in Fig.5. In both cases the SCUBA source is associated with a clump of very red objects, with $K \approx 21$ but $R > 26$, and in the case of Lockman850.1 the IRAM position ties the SCUBA source to the brightest of these clumps. What is so striking about these images is their apparent similarity, and in particular the complexity of the sources at $K$. We are certainly not seeing either an obscured AGN nucleus, or a relaxed elliptical galaxy at intermediate
redshift. In fact, these images are very reminiscent of the complex $K$-band morphologies found for radio galaxies at $z > 3.26$, reinforcing the connection between radio galaxies and the bright sub-mm population in general.

Finally, I note that the one comparably-bright sub-mm source reported from the SCUBA survey of the CFRS has also been identified with an ERO via IRAM interferometry, and again has SED constraints indicating $z = 2 \rightarrow 5$. I conclude, therefore, that if attention is confined to the most luminous sub-mm sources, we find rather little 'diversity' in this population. Whether radio galaxies, cluster companions, or blank field sources, all appear to lie at $z > 2.5$, and are associated with (often complex) EROs.

5 Implications

Given their surface density, extreme ($S_{850\mu m} > 10\text{mJy}$) sub-mm sources can only contribute 5-10 % of the sub-mm background. However if this population is indeed confined to a relatively narrow redshift band (e.g. $3 < z < 5$), their comoving density is $\simeq 1 - 2 \times 10^{-5}\text{Mpc}^{-3}$, the same as the present-day number density of massive ellipticals of comparable mass to radio galaxies ($\geq 4L^*$).

For many years there has been growing evidence that the bulk of the stellar populations in radio galaxies formed at high redshift, $z > 3$. I conclude that the available data indicates that radio galaxies are not special in this regard. Virtually all known luminous sub-mm sources are confined to this
same high-redshift regime, and their number density is sufficient to account for the formation of all massive (≥ $4L^*$) ellipticals. These results suggest that CDM-based models need to be tuned to produce very rapid collapse and conversion into stars of the baryonic gas in the most massive haloes.

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