The near-infrared Hubble diagram for sub-mm galaxies

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Abstract. Determining the nature of the bright sub-mm sources and their role in the process of galaxy formation is likely to be a major focus of extra-galactic research over the next few years. In particular, we would like to know if these sources are the progenitors of today’s massive elliptical galaxies, or alternatively arise from short-lived, albeit spectacular starbursts within haloes of unexceptional mass. This question can be addressed from a number of different directions, one of which is to compare the masses of sub-mm host galaxies with those of other known massive high-redshift objects. Here I make a first attempt to do this by exploring whether the few well-studied sub-mm/mm sources are consistent with the well-established $K-z$ relation for powerful radio galaxies. Out to $z \approx 3$ this appears to be the case, providing evidence that bright sub-mm sources are indeed destined to be massive ellipticals. At higher redshifts there is a suggestion that sub-mm galaxies are significantly fainter at $K$ than their radio-selected counterparts, but at present it is unclear whether this indicates a significant difference in stellar mass or the increasing impact of dust obscuration on the rest-frame light from the sub-mm hosts.

1. Exploring the nature of the sub-mm galaxy population

There are various routes by which to address the question of whether or not sub-mm selected sources are the progenitors of massive elliptical galaxies.

One approach is to determine the extent to which known high-redshift populations are capable of producing strong mm–far-infrared emission. This (relatively efficient) experiment has been performed for powerful radio galaxies (Archibald et al. 2001), quasars (e.g. Isaak et al. 2002), Lyman-break galaxies (e.g. Chapman et al. 2000), and X-ray selected AGN (e.g. Page et al. 2001). The results of these studies indicate that the sort of massive starburst (SFR $\approx 500 - 1000 M_{\odot} \text{yr}^{-1}$) required to produce a bright ($S_{850 \mu m} > 4 \text{mJy}$) sub-mm source is found only in the most massive objects, and generally only at high redshift ($z > 1.5 - 2$). However, it is clearly possible that the sub-mm selected population could be dominated by a somewhat different class of source.

A second approach is to compare the estimated comoving number density of bright sub-mm sources with those of other galaxy populations. As discussed by Scott et al. (2002) the comoving number density of sources with $S_{850 \mu m} > 8 \text{mJy}$ is $\approx 1 \times 10^{-5} \text{Mpc}^{-3}$, comparable to that of extremely red objects at $z \approx 1.5$, and present-day ellipticals with $L > 2 - 3L^*$. However, the interpretation of
such approximate coincidences depends on the assumed typical duration (and frequency) of the starbursts which power the sub-mm emission.

A third approach is to determine how the clustering properties of the sub-mm population compare with those displayed by other galaxy populations. Unfortunately current sub-mm and mm surveys are too small to yield a statistically significant detection of source clustering. However, existing data are certainly consistent with clustering as strong as that displayed by, for example, extremely red objects (Scott et al. 2002), and marginally significant evidence of clustering has been gleaned from cross correlation with Chandra sources (Almaini et al. 2002) and Lyman-break galaxies (Webb et al. 2002).

A fourth approach, which I explore in this brief article, is to investigate how the host galaxies of sub-mm sources compare with other known high-redshift galaxies. Here I have chosen to make this comparison in the near-infrared (i.e. $K$-band) both because many of the sub-mm source host galaxies have only been detected at $K$, and because observed $K$-band brightness currently offers the best means to estimate the masses of high-redshift galaxies.

2. The $K - z$ diagram

The $K - z$ diagram for radio galaxies has been studied and augmented ever since Lilly & Longair (1984) first demonstrated the existence of a tight relation for the 3CR galaxies out to $z \simeq 1$. Recently Eales et al. (1997), van Breugel et al. (1998) and Jarvis et al. (2002) have extended the observed relation to $z > 4$. As shown in Fig. 1, and as discussed by Jarvis et al. (2002), the radio-galaxy data are consistent with the $K - z$ relation expected for a passively-evolving galaxy of (present-day) luminosity $4 - 5L^*$ out to the highest redshifts. Whether pure passive evolution is the true explanation of this relation is not really important for the present purpose. What is clear is that powerful radio galaxies are the most massive known galaxies at high redshift and are undoubtedly destined to be massive ellipticals (given they contain very massive black holes). They thus provide a clear benchmark against which to test the hypothesis that sub-mm selected sources are the progenitors of today's massive ellipticals.

Before attempting to place sub-mm sources on this diagram it is important to realize that the $K$ magnitudes of the radio galaxies have all been measured through large apertures; in Fig. 1 the 3CR and 6C values have been corrected to a metric aperture of 50 kpc, while the $K$ magnitudes given by van Breugel et al. (1998) have been measured through an (in effect very similar) aperture of diameter 4 arcsec. This is important because the continued low scatter in the radio galaxy relation beyond $z \simeq 2.5$ would not be produced if, for example, small aperture magnitudes were simply measured for the brightest visible clumps in these often complex sources. In considering sub-mm sources I have therefore included only objects with measured or reasonably solid estimated redshifts, and for which 4-arcsec aperture or near-total $K$ magnitudes have been measured (or at least attempted) armed with sub-arcsec positional accuracy.

The first three sub-mm sources I have plotted in Fig. 1 are therefore the three galaxies with spectroscopic redshifts from the cluster lens survey, namely SMMJ02399-0134 ($z = 1.06$), 14011+0252 ($z = 2.55$), and 02399-0136 ($z = 2.80$) (Ivison et al. 2000, Smail et al. 2000). The $K$ magnitudes of these three
The $K - z$ diagram for sub-mm sources

Figure 1. Evidence that sub-mm sources display a $K - z$ relation similar to that which is well established for radio galaxies. The open squares indicate the positions of 72 3CR radio galaxies, 57 6C radio galaxies (Eales et al. 1997) and 14 additional high-redshift radio galaxies (van Breugel et al. 1998) on the $K - z$ plane. The solid line is the predicted track of a passively evolving galaxy of constant mass, formed in an instantaneous burst at high redshift ($z > 10$; $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70$km$s^{-1}$Mpc$^{-1}$). The filled symbols indicate my best estimate of the locations of eight of the best-studied bright sub-mm sources on the $K - z$ plane. The first three of these, from the cluster lens survey (Small et al. 2000; Ivison et al. 2000), have been included because they have spectroscopic redshifts as well as solid measured $K$ magnitudes (see text). The next 4 objects are the brightest sub-mm sources from the CUDSS and 8-mJy SCUBA surveys (Eales et al. 1999; Scott et al. 2002), all of which have very accurate positions (from IRAM PdB and VLA interferometry) yielding reliable $K$-band identifications in deep near-infrared images. Redshifts for these sources have been estimated from their 1.4GHz/350GHz flux-density ratios as described in the text. Finally, the lower limit at $z = 4.5$ has been included to indicate the average position of the 3 millimetre sources recently discussed by Dannerbauer et al. (2002).
lensed sources have been de-magnified by factors of 2.5, 2.8 and 2.5 respectively. To explore the relation further I have added the 4 best-studied bright sub-mm sources from the CUDSS and 8-mJy SCUBA surveys (Eales et al. 1999; Scott et al. 2002), all of which have very accurate positions (from IRAM PdB and VLA interferometry) yielding reliable $K$-band identifications in deep near-infrared images. These are CUDSS14A (Gear et al. 2000), Lockman850.1 (Lutz et al. 2001), ELAISN2850.1 and ELAISN2850.2 (Ivison et al. in prep). The redshifts of these objects have been estimated from the mean relation between 350GHz/1.4GHz flux-density ratio and $z$ given by Carilli & Yun (2000) which, in the redshift range of interest, is effectively identical to the extrapolated relation for Arp 220. Finally, I have included a lower limit at $z = 4.5$ to indicate the average position of the 3 millimetre sources recently discussed by Dannerbauer et al. (2002). These sources merit inclusion because, while they still lack $K$-band identifications, they again have positions from mm-wave interferometry of sufficient accuracy to be sure that their counterparts lie below the detection threshold of the existing $K$-band imaging (to convert the published 2-arcsec diameter detection limits to 4-arcsec values I have simply doubled the noise).

Despite the obvious uncertainties it can be seen from Fig. 1 that the sub-mm galaxies display a plausible relationship between $K$ and $z$. Moreover this $K-z$ relation appears indistinguishable to that displayed by the radio galaxies, at least out to $z \approx 3$. At higher redshifts there is a suggestion that sub-mm galaxies are significantly fainter at $K$ than radio galaxies, but at present it is unclear whether this indicates a significant difference in stellar mass or the increasing impact of dust obscuration on the rest-frame light from the sub-mm hosts.

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