Star Formation and AGN in the Early Universe: Quasars in the MAMBO Deep Field Survey

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Abstract. Blank field surveys with SCUBA and MAMBO revealed a population of (sub)mm background galaxies which are massive, $\sim 10^{11} M_{\odot}$ starbursts at median redshifts of ~ 2.5. Due to a radio-selection bias, for one third of the SCUBA/MAMBO sources a clear optical identification or redshift estimate has not yet been possible, but it is likely that these sources lie at redshifts > 3. We find evidence for a different population dominating the counts at $S_{1.2\mathrm{mm}} >$ 10 mJy. The three brightest sources yet found in a wide field MAMBO survey are of lower redshifts (∼0.8 to 1.4), are X-ray bright, radio-loud, and time-variable. Their areal density is significantly higher than that expected from an extrapolation of the flat spectrum radio source population to 1.2 mm. Our preliminary analysis of the the brightest MAMBO source with a thermal submm spectrum (10 mJy at 1.2 mm) suggests it to be a radio-quiet, X-ray bright quasar at $z \sim 3$, thereby is possibly the most luminous starburst ever found.

1 The (Sub)mm Background Resolved

At least half of the cosmic extragalactic energy density (not counting the cosmic microwave background) emerges at far-infrared wavelengths [12,16]. During the past five years, blank field surveys and cluster lens assisted surveys [4], with SCUBA at 850 μm and MAMBO at 1200 μm have resolved a significant fraction of this background into marginally detectable ($\sim$ 3-5 mJy at 1.2mm, a factor 3 brighter at 850μm) sources that are likely to be ultraluminous infrared galaxies at redshifts $\sim 2-4$ [26,19,1,3,8,9]. This previously unknown population of dusty and therefore optically inconspicuous galaxies contributes significantly to the cosmic energy production (and star formation) in the early Universe, although this estimate much depends on the yet ill-constrained dust temperature (and initial mass function).

The high star formation rates ($\approx 1000\,M_{\odot}\mathrm{yr}^{-1}$) implied by the estimated far-IR luminosities ($L_{\mathrm{IR}} \sim 10^{12-13} L_{\odot}$), and the sizes and linewidths ($300-800$ kms^{-1}) of some (sub)mm sources recently detected in CO line emission [22,14] implies that these galaxies are very massive ($\sim 10^{11} M_{\odot}$) systems. The similarity of the co-moving space density of (sub)mm sources and local ellipticals suggests that they are massive spheroids caught during their formation.

The properties and mass function of these high redshift massive galaxies provide robust tests for models of galaxy formation. There is mounting evidence

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[13,22,14] that current models [15,20,28,2] need modifications to reproduce the space densities of the massive high redshift (sub)mm galaxies and their quiescent phases, that must exist since their star formation rates and gas content suggest a low duty cycle of the bright phase. With starburst duty cycles of order 10^8 yr, the extrapolated average volume density of the massive galaxies traced by the MAMBO/SCUBA surveys by far exceeds that predicted by semi-analytic models of galaxy formation through hierarchical mergers [13,14]. With this discrepancy the (sub)mm sources hold important clues to understand the formation and evolution of galaxies. They provide a means to discriminate between an early formation of spheroids via monolithic collapse, and a late formation via hierarchical merging.

Since the (sub)mm galaxies are the most massive of the high redshift star forming galaxy populations, they are also potential beacons to highly biased (i.e., clustered) regions of galaxy formation in the early Universe [27].

2 Redshifts: Missing the High End

While submillimeter and millimeter blank field surveys have by now identified over one hundred sources, spectroscopic redshifts have been difficult to obtain, mainly because of the faintness of their optical/near-IR counterparts and the lack of accurate positions associating them uniquely to an optical source. Accurate source positions could be obtained for about half of the secure (sub)mm sources from deep VLA 20 cm radio maps, which show the most likely counterparts, although ambiguities remain due to the faintness of the radio counterparts (typically $30 - 100\mu$Jy, often detected with low significance) and the apparent clustering of galaxies around the (sub)mm sources.

If the (sub)mm galaxies have radio-to-far-infrared spectral energy distributions similar to those of local star forming galaxies, their observed radio-to-(sub)mm spectral indices provide a rough estimate of the populations' redshift distribution [5]. However, the thereby derived redshift distribution introduces a bias toward low redshifts: due to distance dimming, even our deepest (6.5 μJy rms for Abell 2125) 20 cm radio maps fail to detect counterparts at redshifts larger ~ 3, unless the radio emission is enhanced by an AGN. Therefore currently at least one-third of the MAMBO/SCUBA sources remain without positional or redshift identification. It is this population of (sub)mm galaxies that are most likely to lie at very high (> 3) redshift, and hence provide the most stringent challenges to hierarchical galaxy formation models, and better means must be found to identify them properly.

As an alternative photometric redshift measure, we observed a sample of 23 MAMBO galaxies (with radio counterparts) with SCUBA at 850 μm [11]. Within the uncertainty arising from photometric errors and the degeneracy of dust temperature and redshift, the mm/submm photometric redshift distribution is consistent with the radio-(sub)mm photometric redshift distribution of the larger MAMBO/SCUBA sample (i.e. most sources at redshift 1.5-3.5, median ~ 2.5). However, many of the sources show significantly flatter SEDs than