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The SSA22 Proto-cluster at $z = 3.09$

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Abstract

The measurement of 100 spectroscopic redshifts for the millimeter and submillimeter galaxies (Chapman et al. 2004, Ivison et al. 2004) marks a new era in the study of the most luminous galaxies in the early Universe. Rising to the challenge of this information infusion, we have developed a semi-analytic prescription of the *SCUBA* galaxies, which we use to assess the relative biasing of submm-luminous galaxies over a large volume. We hold our simulations up to the test of the SSA22 proto-cluster region at $z = 3.09$, finding that our predictions have been validated by the discovery of three SCUBA galaxies lying at $z \sim 3.1$. Two of these SCUBA galaxies have also been detected in the CO molecule, verifying their large molecular gas mass, and setting a limit to their (large) dynamical mass. We then use the SSA22 cluster as a fiducial from which to begin a systematic calibration of the submm galaxy overdensities in our full survey.

1.1 Introduction

The diffuse background radiation represents the repository for all the radiation emitted by galaxies over the lifetime of the Universe. Roughly half the energy density in the background comes from radiation at optical and ultraviolet (UV) wavelengths; the remainder arises from a far-infrared (far-IR) component that peaks at wavelengths close to 200 micron (Fixsen et al. 1998, Puget et al. 1996) The first real insight in the origin of the far-IR/submm background came with the commissioning of the SCUBA submm camera on the JCMT. Close to 100% of the submm background has been resolved with the deepest SCUBA maps which exploit a sensitivity boost from gravitational lenses (Smail, Ivison & Blain 1997, Smail et al. 2002, Chapman et al. 2002, Cowie et al. 2002). However, the near-IR/optical faintness of the submm galaxy (SMG) population conspires with the modest positional precision available from the large ($15''$) SCUBA beam and the large surface density of unrelated optically-faint galaxies to render positional coincidence alone inadequate to identify counterparts (Smail et al. 2000; Barger et al. 2000).

By taking advantage of 1.4-GHz radio data from the Very Large Array (VLA) radio telescope (e.g., Richards 2000), ~65% of the SMGs have been pinpointed in optical imagery (Barger et al. 2000, Ivison et al. 2002, Chapman et al. 2001,2003a). With precise radio positions, and the blue sensitivity of the LRIS spectrograph on Keck-I, spectroscopic redshifts have been obtained for $\sim$ 100 members of the millimeter and submillimeter populations (Chapman et al. 2003b, 2004a, Ivison et al. 2004). The redshift distribution of these sources

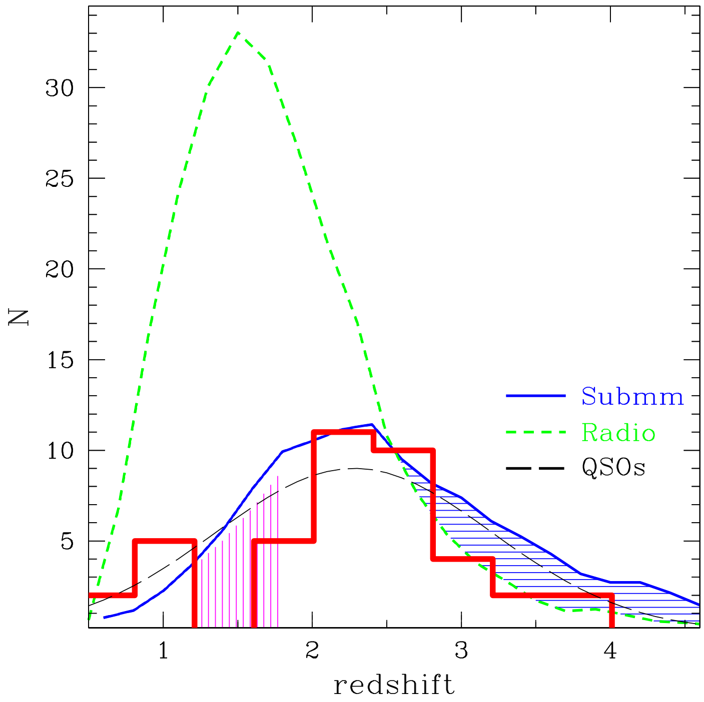

Fig. 1.1. The redshift distribution of the submm galaxy sample from Chapman et al. 2004a (histogram). Model predicted redshift distributions are plotted for submm galaxies with $S_{850\,\mu m} > 5\,\mathrm{mJy}$ (solid line) and radio sources with $S_{1.4\,\mathrm{GHz}} > 30\,\mu\mathrm{Jy}$ (dashed line). The radio-QSO redshift distribution (Shaver et al. 1998) is shown with a light dashed line. The light shaded region highlights the *spectroscopic desert* where no strong line features enter the observable wavelengths. The dark shaded region emphasizes the sources expected to be missed by the requirement for radio detection to pinpoint the SMGs.

peaks at $z \sim 2.4$, as shown in Fig. 1, and is remarkably similar to that of radio-selected QSOs (Shaver et al. 1998).

Statistical samples of SMGs with precise redshifts marks a new era in the study of high-redshift luminous galaxies, allowing the calculation of the temperature and luminosity distributions (Chapman et al. 2004a, Blain et al. 2004a), the use of rest-frame UV and optical line diagnostics to probe the astrophysics (Smail et al. 2003; Smail et al. in preparation), the molecular gas properties through the CO rotational lines (Neri et al. 2003, Greve et al. 2004), and importantly the redshift clustering properties (Blain et al. 2004b).

In this contribution, we have begun a detailed study of the SSA22 proto-cluster region at $z = 3.09$ (Steidel et al. 1998, 2000), with the goal of characterizing the most luminous component of the overdensity, as a fiducial from which to assess the growing number of SMG overdensities being uncovered (Chapman et al. 2004a, Blain et al. 2004b). We compare semi-analytic simulations to observed properties of the SSA22 proto-cluster.

1.2 Results

1.2.1 Simulations of High−z, Luminous Galaxies

An important question to address is how the most luminous galaxy component maps to mass on various scales. In short, how does the SMG population fit into our understanding of the growth of structure in the Universe, and the assembly of the galaxy mass function? Do the SMGs (as the most luminous galaxies in the Universe) always point us to the most overdense regions? Or do they often reflect a brief luminosity burst in relatively normal, L^* galaxies, perhaps reflecting the one major merger such a galaxy likely experiences during its cosmological evolution.

To address these issues, we have undertaken a simulation of representative volumes of the $z = 2$–4 Universe, with the goal of characterizing how the most luminous galaxies map into the mass structures present in large volumes. Most importantly, our simulations do not take the tautological approach of a priori assuming SMGs are extremely massive object, as previous studies have done (e.g., Magliocchetti et al. 2001). In our models, mergers and star formation in efficient bursts are described by semi-analytic prescriptions (C. Baugh, in preparation). This formalism allows for brief luminosity bursts in the course of L^* galaxy assembly to generate submm fluxes detectable by SCUBA-type instruments.

These models allow us to address the types and luminosities of galaxies likely to inhabit different density regions at high−z. The SSA22 proto-cluster at $z = 3.1$, discovered as a spike in the redshift distribution of Lyman-break galaxies (Steidel et al. 1998, 2000), represents the only unbiased discovery of a high-redshift galaxy overdensity. Since it was uncovered as the strongest redshift spike in a distribution of ~ 1000 galaxies at $z \sim 3$ over many fields, the statistical significance of the SSA22 proto-cluster can be assessed relative to the field population.

To use the SSA22 region as a fiducial for our models, we construct a large volume simulation (141 h Mpc on a side) centered at $z \sim 3$. Fig. 2 shows the results of this simulation, and suggests that luminous submm galaxies are expected in increased numbers in the most overdense 10'$\times$10' sub-regions. However, luminous galaxies are also expected in more diffuse environments; the timescales of these 'gas-poor' events are typically shorter than in the overdense regions where fuel supplies are more abundant.

1.2.2 Evidence

Fig. 2 suggests that modest overdensities in the number of submm-luminous galaxies should be signposts to massive high-z proto-clusters. In SSA22, three SMGs have been identified with redshifts $z \sim 3.1$ (Chapman et al. 2004a). Two of these have been detected in CO(4-3) (Chapman et al. 2004b, Greve et al. 2004) indicating molecular gas masses $\sim 5 \times 10^{10}\ M_\odot$, with line widths suggesting dynamical masses in excess of $10^{11}\ M_\odot$. Several other radio sources also been confirmed to lie in the $z = 3.1$ overdensity; in these objects, the lack of submm detection suggests they are either radio-excess AGN or else starbursts with hotter dust temperatures than SCUBA can see.

While the SSA22 proto-cluster was already identified through UV-selected galaxies prior to uncovering the overdensity of SMGs, several other SMG overdensities have been found in other fields (Chapman et al. 2004a), suggesting a strong clustering signal in the SMG population (Blain et al. 2004b), and in two cases being identified with UV-galaxy overdensities (C. Steidel, priv comm). Redshift surveys of SMGs are therefore already providing a

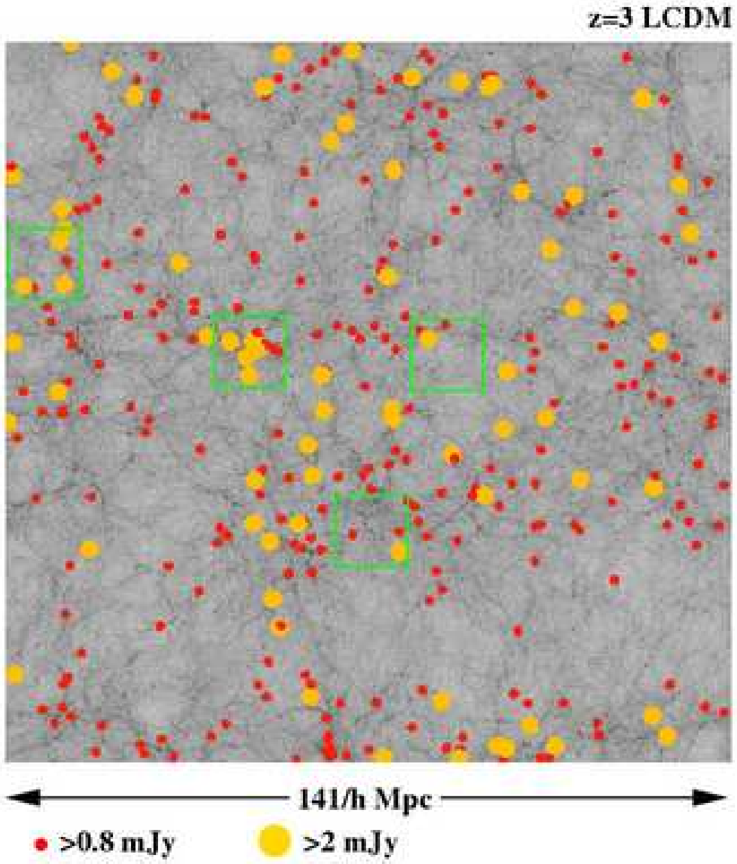

Fig. 1.2. A simulation of a cubic region, 141/h Mpc on a side, centered at z=3 in a LCDM Universe. Luminous galaxies (with $\sim 10^{12}$ and $\sim 10^{13}$ $L_{\odot}$ luminosities, small dots and large dots respectively) are highlighted within the matter distribution. Several regions the size of our 10'×10' survey of SSA22 are highlighted with boxes.

measure of overdense environments in the high redshift Universe. In the same way that the SSA22 proto-cluster significance can be assessed within the LBG distribution (Steidel et al. 1998), the significance of the SMG redshift *spikes* can be assessed within the growing distribution of SMGs with secure redshift identifications. The semi-analytic models, coupled with growing empirical evidence, suggest that a redshift survey of SMGs in a 10'×10' field will quickly identify the largest mass overdensity within the submm-radio selection function (roughly a Gaussian described by $n(z) \propto \exp^{-(z-2.28)^2/1.72}$). We are therefore on the eve of assembling a suite of calibrated tools to map out the large scale structures of the Universe at $z = 2$–4 through the most luminous and biased galaxies – the SCUBA galaxies.

1.3 Conclusions

We have presented initial models of the luminous galaxy component in the z=2–4 Universe. Our detailed characterization of the SSA22 proto-cluster environment provides a fiducial from which to assess and calibrate our models.

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