Abstract. We are currently undertaking a Spitzer GTO program to image \( \sim 30 \) massive lensing clusters at moderate redshift with both IRAC and MIPS. By taking advantage of the gravitational lensing power of these clusters, we will study the population of faint galaxies that are below the nominal Spitzer detection limits. Here, we present a few examples of our science programs.

1. Introduction

The gravitational lensing power of massive galaxy clusters can be exploited to improve the nominal Spitzer detection limits. Clusters at \( z = 0.2 - 0.4 \) typically magnify a background sky area of \( \sim 1 \) arcmin\(^2\) with a magnification factor of \( \gtrsim 5 \) and often up to \( 20 - 30 \), which directly translates into a gain in the signal-to-noise ratio. Furthermore, if the sensitivity is limited by source confusion, gravitational lensing offers a further benefit of reducing the confusion noise by spreading out the background galaxies. For these reasons, Spitzer imaging of massive cluster fields could potentially achieve a depth that is not attainable even in the GOODS fields. In the past, the effectiveness of such a strategy was anticipated for submillimeter observations (Blain 1997), and was successfully demonstrated by a series of SCUBA cluster observations (e.g., Smail et al. 2002).

Motivated by this potential and the success of the submillimeter cluster surveys, we are currently undertaking a Spitzer GTO program to image \( \sim 30 \) massive clusters with both IRAC and MIPS. The main target selection criteria are the following: (1) X-ray luminous, i.e., massive \( (L_X > 7 \times 10^{44} \text{ erg/s}) \); (2) moderate redshift \( (z \sim 0.15 - 0.5) \); (3) low IR background \( (N_H < 3.5 \times 10^{22} \text{ cm}^{-2}) \); and (4) abundance of ancillary data (e.g., HST images, which are necessary to construct accurate cluster mass models). All the clusters will be imaged in the four IRAC bands and in the MIPS 24 \( \mu \)m band; MIPS 70 and 160 \( \mu \)m observations will be carried out for \( \sim 10 \) clusters.

Such a rich data set provides opportunities for many exciting scientific projects. Here, we will present a few examples, concentrating on the lensed sources. In a parallel effort, cluster galaxy evolution is also being studied in combination with a sample of local and high-redshift \( (z \sim 1) \) clusters.

2. 24 \( \mu \)m Sources in the Cluster Cores

Lensing clusters are especially useful for deep imaging at 24 \( \mu \)m because the cluster cores, where the lensing magnification is strongest, are dominated by
early-type galaxies, which are faint at 24 μm. As shown in Figure 1, the majority of the 24 μm sources seen in the cluster core are background lensed sources.

Scientifically, the driver here is to study the population of faint 24 μm galaxies which are below the detection limit of field deep surveys. Most recently, the evolution of 24 μm-selected galaxies have been investigated up to z = 1 (Le Floc’h et al. 2005) and to z = 2.5 (Peréz-González et al. 2005) based on the Spitzer GTO deep survey data of CDF-S and HDF-N using both spectroscopic and photometric redshifts. However, these 24 μm data are not quite deep enough to constrain the shape of the luminosity function below $L^*$ at $z \gtrsim 1$. Furthermore, many of the high-redshift 24 μm galaxies are too faint to detect at 70 and 160 μm, making it impossible to determine their total IR luminosities directly. This cluster program should help address these problems by detecting fainter 24 μm sources and by increasing 70/160 μm detections.

Figure 1 also shows the detection of the triply lensed $z \sim 2.5$ submm galaxy discovered by Kneib et al. (2004a). The three lensed images are faint in the optical, but they are clearly detected in all four IRAC bands and are fairly bright at 24 μm (though still below 1 mJy). Curiously, the spectral energy distribution (SED) measured by IRAC is different from what we saw with the submillimeter/radio sources in the Lockman Hole (Egami et al. 2004). Considering that this source has a high magnification (a total of $\times 45$ with all three images) and that each image further breaks up into substructures with different colors, the IRAC SED might be distorted by differential magnification.

Although most cD galaxies are faint at 24 μm as is the case with Abell 2218, a few cD galaxies in the so-called cooling flow clusters show 24 μm luminosities one to two orders of magnitude larger than those of average cD galaxies. This indicates that these cD galaxies harbor a luminosity source which is blocked from our view at shorter wavelengths.
3. Properties of Stellar Populations at $z = 4 - 5$ and Beyond

The Balmer/4000Å breaks get redshifted into the $K$ band at $z \sim 4$. Therefore, to determine the properties of the underlying stellar population for galaxies at $z \gtrsim 4$ (e.g., age, mass), it is essential to measure fluxes redward of the $K$-band. Presently, IRAC is the only instrument that is sensitive enough to provide such information.

Figure 2 shows the IRAC 3.6 μm detections of three galaxies with spectroscopic redshifts of 4.5 – 5. The magnification factors estimated for these galaxies range from 7 to 10, suggesting that these galaxies would not have been detected without the cluster lensing.

The remarkable potential of Spitzer to probe even higher redshift was demonstrated dramatically by the IRAC detection of a gravitationally lensed $z \sim 7$ galaxy at 3.6 and 4.5 μm [Egami et al. 2005]. This galaxy was first discovered by Kneib et al. (2004b), and is located in the cluster Abell 2218 (Figure 1). Figure 3 shows the HST/NICMOS and Spitzer/IRAC images of the lensed pair. It
is located symmetrically with respect to the critical lines for background sources at \( z \geq 6.5 \), suggesting that the redshift must be at least this high.

Figure 4 compares the SED of component \( b \) with a range of models. Although the redshift has not been confirmed spectroscopically, photometric redshifts derived from Figure 4 range from 6.6 to 6.8, consistent with the lower limit set by the lens model. The figure clearly illustrates the power of IRAC to measure the flux longward of the Balmer break for such a high-redshift galaxy. For this galaxy, we concluded that its underlying stellar population is in the post-starburst stage with an age of at least \( \sim 50 \) Myr (and quite possibly a few hundred Myr), suggesting that a mature system is already in place at this early era. The stellar mass is \( \sim 10^9 M_\odot \), an order of magnitude smaller than typical Lyman break galaxies at \( z = 3 - 4 \).

Considering that this galaxy appears to be in the poststarburst stage, its predecessor is likely to be more luminous at higher redshift, mitigating perhaps the effect of the increased luminosity distance. This presents a further exciting possibility that we may be yet to witness even higher redshift galaxies with *Spitzer*.

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