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Distant ULIRGs in the SWIRE Survey

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Abstract.
Covering ∼49 square degrees in 6 separate fields, the *Spitzer* Wide-area InfraRed Extragalactic (SWIRE) Legacy survey has the largest area among *Spitzer*'s "wedding cake" suite of extragalactic surveys. SWIRE is thus optimized for studies of large scale structure, population studies requiring excellent statistics, and searches for rare objects. We discuss the search for high redshift ultraluminous infrared galaxies (ULIRGs) with SWIRE. We have selected complete samples of $F_{24\mu m} > 200$ μJy, optically faint, candidate high redshift (z>1) ULIRGs, based on their mid-infrared spectral energy distributions (SEDs). These can be broadly categorized as star formation (SF)-dominated, based on the presence of a clear stellar peak at rest frame 1.6μm redshifted into the IRAC bands, or AGN-dominated if the SED rises featureless into the mid-infrared. AGN-dominated galaxies strongly dominate at the brightest 24μm fluxes, while SF-dominated objects rise rapidly in frequency as F_{24} drops, dominating the sample below 0.5 mJy. We derive photometric redshifts and luminosities for SF-dominated objects sampling the z∼1.2-3 range. Luminosity functions are being derived and compared with submm-selected samples at similar redshifts. The clustering, millimeter and IR spectral properties of the samples have also been investigated.

1. *Spitzer* Surveys and ULIRGs

Spitzer has undertaken a suite of extragalactic surveys of varying area and depth which are very well designed to fully investigate the distant mid-infrared Universe. The deepest surveys can reach the highest redshifts but cover very limited volume, while the shallowest surveys can sample the largest volumes and include the largest large-scale structures. The largest area, shallowest depth, tier in the suite is comprised of the First Look Survey (FLS), the Bootes Shallow Survey undertaken by the MIPS and IRAC instrument teams, and SWIRE, one of the first 6 *Spitzer* Legacy surveys. Together these surveys cover about 62 square degrees in 8 separate fields.

Searches for the most extreme, rare, starbursts require large volumes, therefore SWIRE provides the richest hunting ground (Lonsdale et al. 2003, 2004). For example, SWIRE has enough volume to include $\sim$5 $>10^{14}$M$_\odot$ dark matter (DM) halos out to z=1, and about 85 at z=1.5-2.5 (Jenkins et al. 2001). At 24μm SWIRE samples $10^{12}L_\odot$ ULIRGs to redshifts of 1-1.5, depending on SED shape. An $L_{IR} = 10^{13}L_\odot$ system resembling Arp 220, M82 or Mrk 231 can be detected to z$\sim$2.2, 2.8 and 4 respectively. In the longer bands (70 & 160μm) an $L_{IR} = 10^{13}L_\odot$ system cannot be detected beyond about z=1.2-1.4 unless it has an unusually cool SED. However class coadds promise a good way to determine average 70 and 160μm fluxes for distant ULIRGs (Dole et al. 2006; Shupe et al. 2006).

Spitzer searches for extreme, high redshift ULIRGs in the FLS and Bootes fields have focused on objects with high ratios of 24μm/optical flux, and sometimes redness in the 24/8μm color (Houck et al. 2005; Yan et al. 2005). We use a modest limit on L_{IR}/L_{opt} because at z$\sim$1 some local ULIRGs would have lower ratios than adopted by Houck et al. (2005) & Yan et al. (2005), and because in general some SF-dominated objects might be expected to have significant optical flux. We do not restrict $F_{24}/F_{8\mu m}$ because star-forming systems can become quite blue in this color when silicate absorption is present in the 24μm band, or the PAH band redshifts out of it. Instead we use detailed SED-fitting with a library of templates to fully characterize all the objects in the 24μm sample and to reject low redshift systems.

It is important to note that for equal L_{IR} and volume density, *Spitzer* 24μm samples will favor AGN-like objects because they have significantly warmer dust temperature than starburst-dominated objects, therefore we might expect the brightest *Spitzer* samples to be AGN-dominated. This has indeed been found to be the case (Houck et al. 2005; Yan et al. 2005). Therefore more sophisticated techniques, like SED-fitting, are necessary to identfy SF-dominated systems.

2. The SWIRE High Redshift ULIRG Sample

The preliminary sample of high redshift ULIRG candidates has simple inclusion criteria – detection at 24μm at the 5σ level (200 μJy) and optical magnitude $r' > 22$ (Vega) – to optimize completeness of the z>1 sample while minimizing lower redshift interlopers. Detailed SED fitting was then performed for all objects to define the candidate sample of ULIRGs likely to lie at z>1. The final sample therefore does not have a uniform selection function in either r' magnitude, F_{24} or $F_{24}/F_{r'}$.

We used the photometric redshift codes Hyper-z (Bolzonella, Miralles & Pello 2002) and Imp-z (Babbedge et al. 2004), following the methods of Polletta et al. (2006) and Rowan-Robinson et al. (2005), to investigate the nature of the SEDs and, where possible, to derive photometric redshifts. Our overall goals are to characterize the SEDs of all objects within the sample, and estimate redshifts and luminosities, a difficult task with limited libraries and photometric

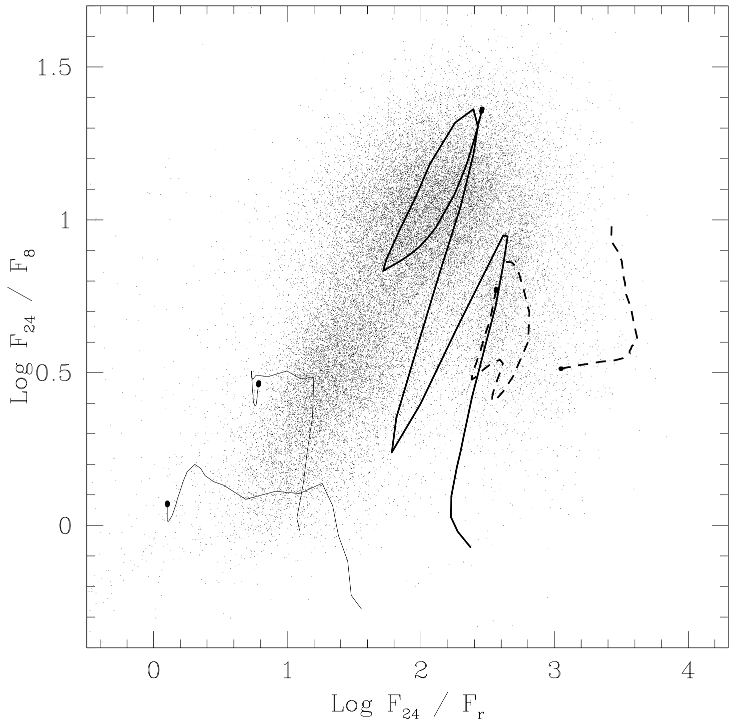

Figure 1. F_{24},$F_{r'}$,F_8 ULIRG 200 μJy sample (dots) color-color diagram. Sample spiral (light lines), starburst-dominated ULIRG (Arp 220) (heavy solid line), and AGN redshift (z=0-4) tracks (heavy dashed lines) are shown; z=0 denoted by a solid dot. Local ULIRGs and starbursts have high (red) values of $F_{24}/F_{r'}$ compared to spirals, and ULIRGs can become quite blue in F_{24}/F_8 at high redshift.

data points (a large fraction of our sample is not detected at our optical flux limits). We explored fits to the extensive local library of Polletta et al., tuning them extensively and iteratively to optimize them to the available data set and to isolate classes of object by redshift and SED shape. Two broad classes dominate the sample: stellar-dominated and AGN-dominated systems; examples are illustrated in Figure 2.

Stellar-dominated objects show a distinct peak, due to the rest-frame 1.6μm H^- opacity minimum in the atmospheres of cool stars. The peak might appear in any of the 4 IRAC bands, however it can be most robustly detected in either the 4.5 or 5.8μm band because there exists a band on either side to confirm that a true peak has been found. For these sources a photometric redshift can be estimated from the IRAC peak shape alone. These sources are thought to be dominated by star-formation in the mid-infrared since they can be well fitted by local starburst and star formation-dominated ULIRG templates.

AGN-dominated objects show either a power-law (PL) rising SED throughout the mid-IR or a convex rising SED shape (Polletta et al.; Alonso-Herrero et al.). Many of the PL sources have similar spectral slope to the well-known local QSO/ULIRG Mrk 231. Objects with a convex torus-like rising SED are similar to the Compton thick QSOs discovered by Polletta et al.. These objects show no direct evidence for starlight in the near- and mid-infrared, and photometeric redshifts are difficult to constrain because the dust temperature is unknown and no spectral features are evident.

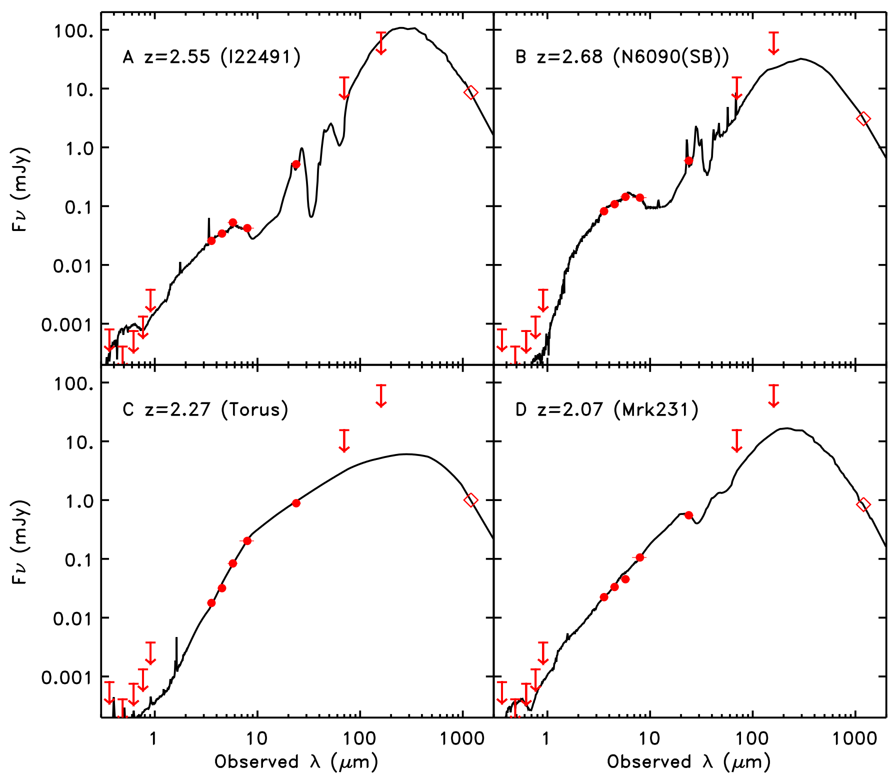

Figure 2. UV-submm spectral energy distributions for 4 SWIRE high redshift ULIRGs. Photometric data points: solid symbols; predictions: open. Top: SF-dominated objects with the NIR stellar peak in an IRAC band (4.5μm in panel A and 5.8μm in panel B), and PAH emission at 24μm. Bottom: AGN candidates fit by a torus model (panel C) and a power-law (panel D). Photometric redshifts are highly uncertain for the AGN. Templates from the library of Polletta et al. (2006).

Here we present results of a study of star formation-dominated objects with a peak in flux in the 4.5 or 5.8μm bands from the 11 sq. degree SWIRE Lockman Hole field, and a spectral shape resembling that expected for stars as in the examples shown in Figure 2. We inspected all images to eliminate confused sources, cosmic ray contamination, *etc.* We find 1000 and 1700 4.5 and 5.8μm peakers respectively, to an $F_{24\mu m}$ flux desity limit of 200 μJy, and 400 / 600 to a limit of 400 μJy. The samples are limited by the sensitivity in the two longest IRAC bands, which is significantly poorer than in the two shorter bands. For this reason the 4.5μm peak sample is limited by SWIRE's 5.8μm sensitivity.

Since very few objects have a 70 or 160μm detection, we cannot directly estimate a bolometric infrared luminosity, but must instead extrapolate from the mid-IR using templates. At 24μm we are sampling restframe 5-15μm, not sampling the main cool dust components that dominate the luminosity of these systems. This leads to a factor of $\sim$10 uncertainty in the bolomertric infrared luminosity, which can be appreciated by comparing the very different starburst-like templates in the upper panels of Figure 2. We present a luminosity-redshift distibution for the Lockman peak sources in Figure 3a where we derive the IR luminosity assuming a modest FIR excess, as in the NGC 6090 template (Silva et al. 1998) in Figure 2b. SWIRE detects $\sim$300 4.5 and 5.8μm peak sources (star formers) per square degree with redshift in the range 1.2-3, the majority with bolometric luminosities over $10^{12.5}$ $L_{\odot}$ even if our conservative estimate is used for the bolometric correction. Preliminary estimates of the luminosity function roughly agree with that derived by Chapman et al. (2005) for sub-millimeter-selected galaxies over a similar redshift range.

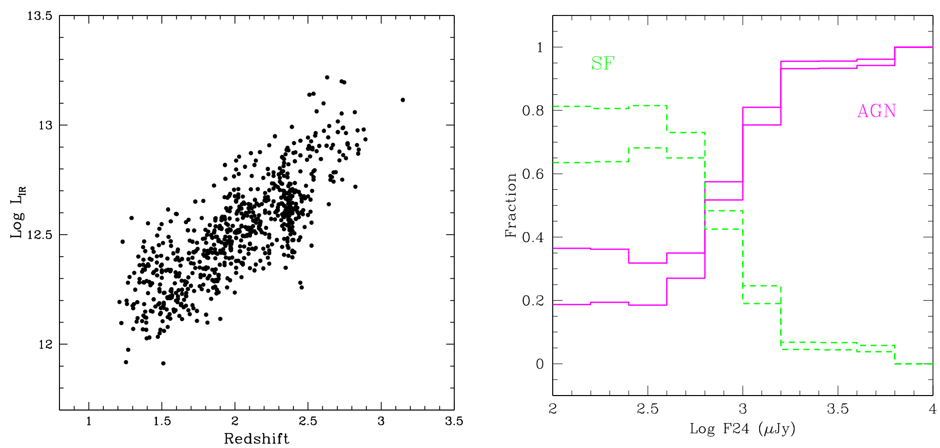

Figure 3. **Left**: Bolometric luminosity *vs.* redshift for SF-dominated 4.5 & 5.8μ peaker ULIRGs in the SWIRE Lockman Hole field. The NGC 6090 template has been adolpted to extrapolate to the far-infrared. A template like Arp 220 would result in luminosities about 10 times larger. **Right**: Distribution of star formation-dominated (dashed histograms) and AGN-dominated ULIRGs (solid histograms) as a function of 24μm flux. The two histograms for each subsample reflect the range of uncertainty in the classifications. AGN dominate bright samples while starbursts become strongly dominant below 600 μJy.

Finally in Figure 3b we illustrate the dependence of power source on 24μm flux density. Here we have classified the entire high redshift Lockman Hole ULIRG sample. Some sources have ambiguous types due to lack of enough bands with good photomeric detections, therefore we show minimum and maximum histograms for the two populations types. Clearly, AGN dominate the brightest samples, explaining why early IRS observations of 24μm-bright distant ULIRG samples show little PAH emission (Yan et al. 2005; Houck et al. 2005).

It is clear that to discover large samples of starburst-dominated ULIRGs one only needs drop the 24μm flux density threshold a little below 1 mJy, and by 400 μJy, starburst-dominated ULIRGs outnumber AGN by far.

3. Conclusions and Follow-up Studies

SWIRE has detected tens of thousands of z>1 ULIRGs and, amongst these, starbursts can be well-separated from objects with AGN-dominated mid-IR SEDs through detection of the 1.6μm rest-frame H^-opacity minimum feature, expected in the atmospheres of evolved stars, redshifted into the IRAC bands. Focusing on the 4.5 and 5.8μm peakers because they can be better defined than 3.6 or 8μm peakers, we find 2700 $F_{24} > 200\mu$Jy ULIRGs in the z=1.2-3 range in the Lockman Hole, the most distant with far-infrared luminosities exceeding $10^{13}L_\odot$ if a conservative bolometric correction is adopted. If we were to assume an Arp 220 SED instead, the estimated FIR luminosities would increase by a factor of ~10. Preliminary results using class coadds of IRAC-peaker sources indicate a modest SED like NGC 6090 is appropriate for many of these systems (Shupe et al. 2006).

The samples are flux limited at 4.5 and/or 5.8μm as well as at 24μm, both near 40μJy because the longer wavelength sensitivity dominates the ability to identify an object as a peaker. These limits translate to mass limits in evolved stars of 2-7 $10^{11}M_\odot$, depending on redshift and the ages of the stellar populations used in the modeling (Berta et al., in preparation). The large masses being found in stellar populations, coupled with the modest far-infrared excesses indicated by the class coadds, suggest that these systems may be past the peak of their initial star formation epoch, on their way to becoming massive ellipticals.

Observations with IRS on board *Spitzer* of a small sample of SWIRE IRAC-peakers confirm that they are starburst-dominated by virtue of detection of strong PAH features; conversely X-ray selected AGN show IR spectra consistent with power-law or torus-like mid-IR SEDs (Weedman et al., in preparation). Furthermore SWIRE IRAC-peakers have a higher detection rate at 1.2mm with MAMBO (Lonsdale et al., in preparation) than an AGN-dominated sample from the FLS survey (Lutz et al. 2005), probably confirming a larger mass in cool dust amongst the starburst-dominated IRAC peaker sample.

The clustering of SWIRE 4.5 and 5.8μm peakers has been investigated by Farrah et al. (2006), with significant detections of the correlation length in two redshift slices. The study provides evidence that these objects may reside in halos of mass $\sim 10^{13}M_\odot$, and may evolve to inhabit poor to rich clusters.

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