Ultraluminous and Hyperluminous Infrared Galaxies in the SDSS, 2dFGRS and 6dFGS

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ABSTRACT

We present a result of cross-correlating the Infrared Astronomical Satellite Faint Source Catalogue (IRAS FSC) with the spectroscopic catalogues of galaxies in the Fourth Data Release of Sloan Digital Sky Survey (SDSS), the Final Data Release of 2dF Galaxy Redshift Survey (2dFGRS) and the Second Data Release of 6dF Galaxy Survey (6dFGS). We have identified 324 ultraluminous infrared galaxies (ULIRGs) including 190 newly discovered ULIRGs, and 2 hyperluminous infrared galaxies (HLIRGs). Adding these new ULIRGs, we increase the number of known ULIRGs by about 30 per cent. The reliability of the cross-correlation is estimated using the likelihood ratio method. The incompleteness of our sample introduced by the identification procedure in this study is estimated to be about 5 per cent. Our sample covers the redshift range of z=0.037−0.517 with a median redshift of \bar{z}=0.223, which is larger than that (\bar{z}=0.184) of the sample of previously known ULIRGs.

Key words: galaxies: active – galaxies: general – infrared: galaxies

1 INTRODUCTION

The interest in luminous infrared galaxies, in particular ultraluminous infrared galaxies1 (ULIRGs) and the hyperluminous infrared galaxies2 (HLIRGs), has been growing since the launch of Infrared Astronomical Satellite (IRAS; Neugebauer et al. 1984) in 1983. A great deal of effort has been made to understand the origin of the enormous infrared luminosities of these populations and the time evolution of individual ULIRGs, which are summarised in Sanders & Mirabel (1996) and Lonsdale, Farrah, & Smith (2006). It is generally accepted that dust heated by some combination of starburst and active galactic nuclei (AGN) activity is responsible for the IR luminosity (e.g. Farrah et al. 2001). However, it is not yet clear which is the dominant power source. There are several suggestions for the time evolution of individual ULIRGs. Sanders et al. (1988a) suggested that ULIRGs may be an initial, dust-shrouded stage of optical QSOs, while Farrah et al. (2001) proposed that ULIRGs are not a simple transition stage from galaxy mergers to QSOs but evolve through diverse paths. On the other hand, several authors suggested that ULIRGs might evolve into moderately massive (L∗) field ellipticals (Kormendy & Sanders 1992; Genzel et al. 2001; Tacconi et al. 2002).

Infrared space telescopes have driven much recent progress (see Genzel & Cesarsky 2000 and Verma et al. 2003 for a review). Genzel et al. (1998) showed that several diagnostic lines in mid-infrared spectra using Infrared Space Observatory (ISO; Kessler et al. 1996) are very powerful in characterizing the power source of ULIRGs. They concluded that most ULIRGs (80%) are powered by starbursts, but at least half of their sample require both a starburst and an AGN. Similar results are found in Lutz et al. (1998) and Rigopoulou et al. (1999). Moreover, Tran et al. (2001) showed that ULIRGs with LIR < 10^{12.4} L⊙ are mostly...

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1 We define ULIRGs as the galaxies whose infrared (1–1000 μm) luminosities are greater than 10^{12} L⊙.
2 We define HLIRGs as the galaxies whose infrared luminosities are greater than 10^{13} L⊙.
starburst dominated, while ULIRGs with $L_{\nu} > 10^{12.4}L_\odot$ are more likely to contain AGN. The Spitzer Space Telescope (Werner et al. 2004) and submillimetre/millimetre-wave cameras such as SCUBA are now extending samples of ULIRGs to higher redshifts ($z > 1$). Several authors (Houck et al. 2003; Lutz et al. 2003; Yan et al. 2003) took spectra of optically faint and infrared luminous population using Spitzer, detecting broad spectral features such as PAH (Polycyclic Aromatic Hydrocarbon) emission and silicate absorption. They showed that the majority of these population are at high redshift ($z \sim 2$) and have mid-infrared spectral shapes similar to local AGN-dominated ULIRGs.

Since the publication of the IRAS Point Source Catalogue (1988; hereafter PSC) and the IRAS Faint Sources Catalogue – Version 2 (Moshir et al. 1992, hereafter FSC92), many wide-area redshift survey follow-up campaigns have been conducted. In total, these have led to a heterogeneous compilation of a few hundred ULIRGs from sources such as the IRAS 1.2 Jy Redshift Survey (Strauss et al. 1990, 1992; Fisher et al. 1993), the IRAS 1 Jy Survey of ULIRGs (Kim & Sanders 1998), the QDOT all-sky IRAS galaxy redshift survey (Lawrence et al. 1999), the Point Source Catalogue redshift survey (Saunders et al. 2000), the FIRST/FSC sample (Stanford et al. 2000), and the Revised Bright Galaxy Sample (Sanders et al. 2003). The small area surveys are summarised in Sanders & Mirabel (1996) and Lonsdale, Farrah, & Smith (2006). The majority of ULIRGs found in all sky redshift surveys are from the nearby universe ($z < 0.5$) and have abundant multi-wavelength data. Such objects are useful prototy pes for the study of high redshift infrared luminous galaxies. However, these redshift surveys are still far from being a complete spectroscopic survey of all IRAS sources. Therefore, many ULIRGs remain undiscovered in FSC92.

More recent galaxy redshift surveys such as the Sloan Digital Sky Survey (SDSS, York et al. 2000), the 2dF Galaxy Redshift Survey (2dFGRS, Colless et al. 2001) and the 6dF Galaxy Survey (6dFGS, Jones et al. 2004) have provided redshifts for much larger samples of galaxies. These data will clearly be very useful for finding new ULIRGs in FSC92, which has been attempted by several st udies (Cao et al. 2006; Goto 2003; Pasquale, Kaufmann, & Heckman 2003). However, Goto (2003) and Pasquale, Kaufmann, & Heckman (2003) cross-correlated the IRAS sources with the SDSS spectroscopic sample of galaxies using a circular matching tolerance instead of using a positional error ellipse of the IRAS sources. Cao et al. (2006) performed a similar cross-correlation using the formal positional error ellipses of the IRAS sources, but they used only the Second Data Release of SDSS.

In this paper we present a search for ULIRGs and HLIRGs from a cross-correlation of FSC92 with the most recent spectroscopic catalogues of galaxies in SDSS, 2dFGRS and 6dFGS, using positional matches in the IRAS error ellipses. The data used for the cross-correlation and the identification algorithm for ULIRGs and HLIRGs are presented in Section 2. Our main results are presented in Section 3, and are discussed in Section 4. We summarize and conclude in Section 5. Throughout this paper, we assume that $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 0.3$ and $\Lambda = 0.7$.

## 2 IDENTIFICATION OF ULIRGS AND HLIRGS

### 2.1 The Samples and Cross-Correlation

We cross-correlated the IRAS sources in FSC92 with the spectroscopic sample of galaxies in the Fourth Data Release of SDSS [Adelman-McCarthy et al. 2003, hereafter SDSSDR4], the Final Data Release of 2dFGRS (Colless et al. 2001, hereafter 2dFGRS, DR4) and the Second Data Release of 6dFGS (Jones et al. 2003, hereafter 6dFGSDR2). The FSC92 contains about 173,000 infrared sources with measured fluxes at 12 $\mu$m, 25 $\mu$m, 60 $\mu$m and 100 $\mu$m. The SDSSDR4 and the 2dFGRS-DR4 have a similar median depth of $\pm 0.11$. The SDSSDR4 contains about 473,000 galaxies over 4,800 deg$^2$, and the 2dFGRS-DR4 contains about 246,000 galaxies over 2,000 deg$^2$. The 6dFGSDR2 which contains about 89,000 galaxies, covers a wider area ($\sim 13,600$ deg$^2$) than the other surveys, but has a shallower median depth of $\pm 0.05$.

The positional uncertainties of the IRAS sources are different for the in-scan direction and the cross-scan direction (typically 5$''$ for the in-scan direction and 16$''$ for the cross-scan direction, 1 $\sigma$), and vary from source to source (1"−13" for the in-scan direction, or minor axis of positional uncertainty ellipse and 3"−55" for the cross-scan direction, or major axis of positional uncertainty ellipse, 1 $\sigma$). The positional uncertainties of the optical identifications themselves are negligible in comparison. We use the positional uncertainty ellipse of FSC92 to find matching counterparts of the IRAS sources, instead of using a circular matching tolerance (to be discussed in Section 2.3). If a galaxy in a redshift survey lies within 3 $\sigma$ positional uncertainty ellipse of the IRAS source, we regard it a match. As a result of this matching, we find that 8382, 2091 and 10197 IRAS sources have optical counterparts in the SDSSDR4, 2dFGRS-DR4 and 6dFGSDR2, respectively. Some IRAS sources (615 for SDSSDR4, 201 for 2dFGRS-DR4, and 91 for 6dFGSDR2) have more than two galaxies within 3 $\sigma$ error ellipse. In these cases, we computed the “Likelihood Function (LR)” (Sutherland & Saunders 1992) to be discussed in 2.3) of each association, and selected a more appropriate galaxy with the larger value of LR as an optical counterpart. In total, we compiled a list of 19,380 sources by collecting all matched sources from our disparate galaxy redshift surveys.

### 2.2 Selection Criteria

We used the following steps in order to identify bona-fide ULIRGs and HLIRGs from the list of all matched sources:

(i) For 19,380 sources in the list of all matched sources, we calculated the IR luminosities using the IRAS 60 $\mu$m fluxes and the redshifts of galaxies on the assumption that the ULIRGs and HLIRGs have M82 starburst Spectral Energy Distributions (SEDs). A substantial fraction of the IRAS sources have upper limit fluxes at 12 $\mu$m, 25 $\mu$m and 100 $\mu$m, so we use this single-band selection to obtain a less

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3 The earlier version of this survey is the Bright Galaxy Survey (Soifer et al. 1986, 1987, 1989; Sanders et al. 1992).
heterogeneous final catalogue (to be discussed in Section 2.3).

(ii) We selected the sources for which their 60 μm flux qualities are “high” or “moderate” (Mosher et al. 1992) in order to restrict our analysis to those sources with reliable 60 μm detections, obtaining 19,335 sources.

(iii) Of the 19,335 reliable sources, we classified 483 sources as ULIRG candidates (IR luminosities greater than 10^{12} L_☉), and classified 14 sources as HLIRG candidates (IR luminosities are greater than 10^{13} L_☉).

(iv) We then assessed the quality of the redshift for the ULIRG and HLIRG candidates. We required a redshift confidence of ≥0.65 for the SDSSDR4, a redshift quality of ≥3 for the 6dFGS DR2, and a redshift quality is equal to 3 or 4 for the 6dFGS DR2. See each data release paper for the descriptions of these redshift quality parameters. On this basis, we secured 333 ULIRG and no HLIRG candidates with acceptable redshift qualities.

(v) We used the NASA/IPAC Extragalactic Database (NED) Near Position Search in order to reject chance coincidences of IRAS sources for which optical counterparts are already listed in the literature. We rejected 13 ULIRG candidates (two sources moved to a list of HLIRGs), and added 4 sources (to be discussed in Section 2.3). Our redshifts for these four are confirmed in the literature, although their redshift qualities do not satisfy our criteria. Finally we found 324 ULIRGs and 2 HLIRGs (the final two HLIRGs will be discussed in Section 4.3).

Table 1. The IRAS data for the Final Sample of ULIRGs

| FSC NAME ID | RA (J2000) | Dec (J2000) | 12μm (Jy) | 25μm (Jy) | 60μm (Jy) | 100μm (Jy) | Flux Qual |
|-------------|------------|------------|-----------|-----------|-----------|-----------|----------|
| F00050−3259* | 00 07 34.6 | −32 43 03 | 0.066 (0.018) | 0.144 (0.042) | 0.222 (0.045) | 0.758 (0.220) | 1131 |
| F00091−0738 | 00 11 43.3 | −07 22 05 | 0.071 (0.020) | 0.215 (0.054) | 2.626 (0.184) | 5.251 (0.202) | 1232 |
| F00091−3905* | 00 11 42.3 | −39 49 15 | 0.106 (0.030) | 0.125 (0.038) | 0.316 (0.047) | 0.756 (0.227) | 1131 |
| F00095−5948* | 00 11 58.8 | −59 31 28 | 0.074 (0.014) | 0.052 (0.010) | 0.313 (0.034) | 0.681 (0.123) | 1132 |
| F00184−3318* | 00 20 57.7 | −33 14 28 | 0.105 (0.028) | 0.120 (0.035) | 0.334 (0.047) | 0.613 (0.141) | 1132 |
| F00256−0208 | 00 28 14.4 | −01 51 47 | 0.108 (0.031) | 0.323 (0.099) | 0.602 (0.060) | 0.611 (0.147) | 1132 |
| F00285−3140 | 00 31 03.0 | −31 24 18 | 0.144 (0.042) | 0.141 (0.041) | 0.389 (0.051) | 0.688 (0.199) | 1132 |
| F00318−3137* | 00 34 16.0 | −31 21 04 | 0.108 (0.030) | 0.167 (0.048) | 0.257 (0.062) | 0.563 (0.158) | 1132 |
| F00335−2732 | 00 35 59.2 | −27 15 42 | 0.144 (0.045) | 0.632 (0.069) | 4.294 (0.472) | 3.207 (0.225) | 1332 |
| F00406−3127 | 00 43 03.0 | −31 10 53 | 0.060 (0.016) | 0.091 (0.025) | 0.717 (0.057) | 0.994 (0.169) | 1132 |

Column descriptions: (1) The IRAS object name in the FSC92. Asterisks represent the sources that are identified as ULIRGs for the first time in this study; (2-4) The identification, the redshift, and the redshift confidence value in SDSSDR4; (5-7) The identification, the redshift, and the redshift quality parameter in 6dFGS DR2; (8-10) The identification, the redshift, and the redshift quality parameter in 2dFGRS DRF; (11) Finally accepted optical counterpart (1–SDSSDR4, 2–6dFGS DR2, 3–2dFGRS DRF).

Table 2. ULIRGs found in SDSSDR4, 2dFGRS DRF and 6dFGS DR2

| NAME ID | z | zconf ID | ID | z | Q | Final |
|---------|---|----------|---|---|---|------|
| F00050−3259* | 00 07 34.6 | −32 43 03 | 0.066 (0.018) | 0.144 (0.042) | 0.222 (0.045) | 0.758 (0.220) | 1131 |
| F00091−0738 | 00 11 43.3 | −07 22 05 | 0.071 (0.020) | 0.215 (0.054) | 2.626 (0.184) | 5.251 (0.202) | 1232 |
| F00091−3905* | 00 11 42.3 | −39 49 15 | 0.106 (0.030) | 0.125 (0.038) | 0.316 (0.047) | 0.756 (0.227) | 1131 |
| F00095−5948* | 00 11 58.8 | −59 31 28 | 0.074 (0.014) | 0.052 (0.010) | 0.313 (0.034) | 0.681 (0.123) | 1132 |
| F00184−3318* | 00 20 57.7 | −33 14 28 | 0.105 (0.028) | 0.120 (0.035) | 0.334 (0.047) | 0.613 (0.141) | 1132 |
| F00256−0208 | 00 28 14.4 | −01 51 47 | 0.108 (0.031) | 0.323 (0.099) | 0.602 (0.060) | 0.611 (0.147) | 1132 |
| F00285−3140 | 00 31 03.0 | −31 24 18 | 0.144 (0.042) | 0.141 (0.041) | 0.389 (0.051) | 0.688 (0.199) | 1132 |
| F00318−3137* | 00 34 16.0 | −31 21 04 | 0.108 (0.030) | 0.167 (0.048) | 0.257 (0.062) | 0.563 (0.158) | 1132 |
| F00335−2732 | 00 35 59.2 | −27 15 42 | 0.144 (0.045) | 0.632 (0.069) | 4.294 (0.472) | 3.207 (0.225) | 1332 |
| F00406−3127 | 00 43 03.0 | −31 10 53 | 0.060 (0.016) | 0.091 (0.025) | 0.717 (0.057) | 0.994 (0.169) | 1132 |

Column descriptions: (1) The IRAS object name in the FSC92. Asterisks represent the sources that are identified as ULIRGs for the first time in this study; (2-3) Right ascension and declination; (4-7) The IRAS flux density (and its uncertainty) at 12μm, 25μm, 60μm and 100μm; (8) The IRAS flux density qualities at each band (1—upper limit, 2—moderate quality, 3—high quality).
Table 3. The Final Sample of ULIRGs

| FSC NAME | Final logLIR (L⊙) | log(LR) | Class |
|----------|------------------|---------|-------|
| F00050−3259* | 0.2855 | 12.12 | 5/V |
| F00091−0738 | 0.1178 | 12.30 | 7/I |
| F00109−1390* | 0.2535 | 12.14 | 7/I |
| F00095−5948* | 0.2349 | 12.06 | 7/I |
| F00184−3331* | 0.2387 | 12.10 | 5/IIIa |
| F00256−0208 | 0.2770 | 12.52 | 7/V |
| F00285−3140 | 0.2166 | 12.07 | 4/I |
| F00318−3137* | 0.2846 | 12.18 | 7/V |
| F00335−2732 | 0.0686 | 12.01 | 7/I |
| F00406−3127 | 0.3425 | 12.82 | 5/V |

Column descriptions: (1) The IRAS object name in the FSC92. Asterisks represent the sources that are identified as ULIRGs for the first time in this study; (2) Finally accepted redshift from galaxy redshift survey; (3) Infrared luminosity calculated in this study; (4) Likelihood ratio; (5) Morphological class using Lawrence classification (L) and Surace classification (S). See the description in the end of this section.

Adopted redshifts, IR luminosities, log (LR) and morphological classes (to be discussed at the end of this section) are listed in Table 3.

Figure 4 shows a sample of 3’ × 3’ finding charts (left hand panels) for the final sample of ULIRGs extracted from the SDSS gri composite images or the SuperCOSMOS scans of r′ survey plates. The contour plot for each ULIRG using the SDSS r-band images or the SuperCOSMOS r′ images is also presented in Figure 4 (right hand panels). Using Figure 4 we classify the interaction types of the ULIRGs in the final sample. The ULIRGs are classified according to the modified version of the interaction classification schemes of Lawrence et al. (1999), hereafter Lawrence classification (see, e.g., Farrah et al. 2001) and of Surace (1998), hereafter Surace classification (see, e.g., Veilleux, Kim & Sanders 2002), as are summarised in Table 4. The results of the classification are given in the last column of Table 3. The complete versions of Table 1, Table 2, Table 3 and Figure 1 are available only in the electronic issue. A brief discussion of some ULIRGs is given in Appendix A that is available in the electronic issue.

2.3 Reliability of Identifications

A variety of definitions of ULIRGs have been used in the literature, and depend on the minimum luminosity, the adopted spectral energy distributions and the cosmology (L⊙−1000 ≳ 10^{12} L⊙ with H₀ = 75 km s⁻¹ Mpc⁻¹ and q₀ = 0.0 for Sanders & Mirabel 1996, Kim & Sanders 1998, and Goto 2003), L₉₀ ≳ 10^{10.75} L⊙ with H₀ = 100 km s⁻¹ Mpc⁻¹ and q₀ = 0.5 for Clements et al. 1996b, L₉₀ ≳ 10^{12} L⊙ with H₀ = 50 km s⁻¹ Mpc⁻¹ and Ω = 1 for Lawrence et al. 1999). In order to check the reliability of our selection criteria of ULIRGs, we compiled 636 known ULIRGs taken mostly from wide area survey data (Leech et al. 1994, Cloves et al. 1995, Murphy et al. 1996, Clements et al. 1996b, Duc, Mirabel & Maza 1987, Kim & Sanders 1998, Clements, Saunders & McMahon 1999, Stanford et al. 2004, Sanders et al. 2005, Rigopoulou et al. 1999, Goto 2003, Cao et al. 2006). We then applied the same procedure given in Section 2.2 to select ULIRGs in this sample of known ULIRGs. Of these known ULIRGs from the literature, we found 291 reliable sources in step (ii) of Section 2.2. A total of 345 known ULIRGs were not found since they were neither observed in the redshift surveys of this study nor included in FSC92. After the final identification step in Section 2.2 we found 131 known ULIRGs in our final sample of ULIRGs, and failed to find a total of 160 ULIRGs. The reasons our having missed these 160 known ULIRGs are categorised as follows:

(i) Different redshifts (F00415−0737, F01031−2255, F01082−2452, F03014−2026, F03193−2224, F03448−2628, F08509−1504, F01122+4943, F20087−0308, F20109−3003, F20175−4756, F23515−2917): For the sources in this category, the redshifts used in this study are different to (and almost always much lower than) those in the literature. Therefore, the IR luminosities calculated in this study are not large enough to be selected as ULIRGs in this study. Some sources have high redshift qualities (F00415−0737, F08509−1504, F01122+4943, F20109−3003), while the redshift qualities for the others are low. The redshift of F01031−2255 used in this study is larger than that in the literature, but it is not included in the final sample of ULIRGs due to its low redshift quality.

(ii) Different optical counterpart galaxies (F03202−0001, F08007+3928, F09346+3911, F12527−0306, F14390+6209, F14475+0155, F14546+0338, F15182+3023, F21368+1006, F22011+0017, F23051−0110): The optical counterpart galaxies of these IRAS sources in this study are different from the galaxies in the literature, as are their redshifts.

(iii) Different 60µm fluxes (F00444−1803, F03920+6134, F11087+5351, F14170+4545, F14351−1954, F14575+3256, F18520−5048): The IR luminosities of these sources are not greater than 10^{12} L⊙ since the 60 µm fluxes of these sources used in this study (from FSC92) are lower than the fluxes used in the literature (mostly from FSC).

(iv) Marginal ULIRGs (F12495−3414, F13156+0435, F14378−2604, F22509−0040): Since the L₉₀ luminosities of all four sources are slightly less than 10^{12} L⊙, they were classified as further marginal/possible ULIRGs in Lawrence et al. (1999). Similarly, their IR luminosities calculated in this study are in the range of 10^{11.84} − 10^{11.97} L⊙, therefore they are not classified as ULIRGs in this study.

(v) Low qualities of redshifts (F00406−3127, F10026−0022, F14207−2002, F14485−2434, F22123−2025): These sources satisfy the selection criteria up to step (iii) of Section 2.2. However, they fail to satisfy the criteria in step (iv) of Section 2.2 due to their low redshift qualities. Although the redshift qualities of F00406−3127, F14485−2434 and F22123−2025 are low, these redshifts are same as those quoted in the literature. Therefore we include these three sources in the final sample of ULIRGs. F14207−2002 is not a known ULIRG, but its redshift in this study is same as that of Allen et al. (1991). Therefore we also include F14207−2002 in the final sample of ULIRGs. However, F10026−0022 was identified as a ULIRG in Goto (2003) using the same SDSS data with low quality of redshift as in
Figure 1. The $3' \times 3'$ finding charts (left in each panel) and contour plots (right in each panel) of 324 ULIRGs identified in this study. The finding charts centred on IRAS source positions are extracted from the SDSS $gri$ composite images or the SuperCOSMOS scans of $r_F$ survey plates. North is up, and the East is to the left. The ellipse represents $3\sigma$ IRAS positional uncertainty. The optical counterpart in the redshift surveys is marked by square indicating the size, orientation and location of the contour plot in the finding chart. The IRAS object names are presented in the bottom left corner, and asterisks represent the newly identified ULIRGs in this study. The contour plots centred on optical counterparts represent the intensities of ULIRGs in the SDSS $r$-band images or the SuperCOSMOS $r_F$ images. The size of each contour plot is 40 kpc $\times$ 40 kpc. The contour levels increase from the sky level ($I_{\text{sky}}$) to the peak value ($I_{\text{max}}$) by factors $10^{(I_{\text{max}}-I_{\text{sky}})/8}$. The orientation is indicated by the arrows and the thick, horizontal bar represents 5 arcsec in each contour plot.
Table 4. The interaction classification scheme of ULIRGs used in this study

| Scheme | Class | Description |
|--------|-------|-------------|
| Lawrence | 0 | Isolated source with no signs of interaction or merging |
| classification | 1 | Source with a faint companion (2−4 mag fainter than the source) in the range of 40−200 kpc |
| | 2 | Source with a bright companion (less than 2 mag fainter than the source) in the range of 40−200 kpc |
| | 3 | Source with a faint companion less than 40 kpc |
| | 4 | Source with a bright companion less than 40 kpc |
| | 5 | Source interacting with a companion and showing signs of interaction |
| | 6 | Merger/More than two nuclei in common envelope |
| | 7 | Merger/Single nuclei in common envelope |
| Surace | I | First approach – Unperturbed and separated galaxies with no signs of interaction or merging |
| classification | II | First contact – Overlapped disks but no strong bars and tidal tails |
| | IIIa | Pre-merger a – Two recognisable nuclei with strong signs of interaction and separated more than 10 kpc |
| | IIIb | Pre-merger b – Two recognisable nuclei with strong signs of interaction and separated less than 10 kpc |
| | IV | Merger – Only one nucleus seen with strong tidal features |
| | V | Old merger – No direct signs of tidal features but disturbed central morphology |

this study. Therefore we reject it from the final catalogue of ULIRGs.

(vi) Underluminous ULIRGs (F00090−0054, F08112+3039, F08322+3609, F09045+3943, F16134+2919, F21341−0033): These sources are the FIRST-FSC sample of Stanford et al. (2000). They did not use a strict minimum infrared luminosity to identify ULIRGs. The far-infrared (FIR) luminosities for these sources in Stanford et al. (2000) are in the range of 10^{11.27} − 10^{11.85} L_{⊙}, which is similar to the minimum FIR luminosity of ULIRGs in Sanders & Mirabel (1996). Similarly, these sources are not selected as ULIRGs in this study due to our low estimates for their IR luminosities (10^{11.44} − 10^{11.99} L_{⊙}).

(vii) Different SEDs (F21219−1757): This source was classified as a ULIRG in Kim & Sanders (1998) with log(L_{IR}/L_{⊙})=12.06. However, the IR luminosity calculated in this study is log(L_{IR}/L_{⊙})=11.86 which does not satisfy the ULIRGs criteria, although the redshift and IRAS flux densities used in this study are same as those in Kim & Sanders (1998). This is because we used M82 starburst SED to calculate the IR luminosity which may not be appropriate for low luminosity QSOs such as this. If we use AGN dominated SED of NGC 1068 to calculate the IR luminosity for this source, we obtain the IR luminosity of log(L_{IR}/L_{⊙})=12.14, satisfying the ULIRGs criteria.

(viii) Using upper limit flux (115 objects): These sources were classified as ULIRGs in Goto (2005) and Cao et al. (2006). Although most IRAS galaxies have upper limit fluxes at 12μm and 25μm (to be discussed in the end of this section), Goto (2005) calculated the IR luminosities of IRAS sources by treating the flux upper limits as detections. Similarly, three sources for which 100μm flux densities are “upper limits” were found to be ULIRGs in Cao et al. (2006) by assuming the 100μm upper limit is obtained. These calculations can clearly result in overestimates for the IR luminosities of IRAS galaxies. These sources are not selected in our study as ULIRGs due to their low IR luminosities of 10^{10.60} − 10^{11.99} L_{⊙}.

In summary, all 160 known ULIRGs that are not identified in this study have appropriate reasons not to be selected as ULIRGs except for only one source (F21219−1757). Therefore we conclude that our ULIRGs selection criteria are reliable and good enough to identify nearly all known ULIRGs.

Goto (2005) performed a cross-correlation of FSC92 with the spectroscopic catalogues of galaxies in the SDSS Third Data Release (SDSSDR3), and identified 178 ULIRGs and 3 HLIRGs. Since the SDSSDR4, which we used for our cross-correlation in this study, contains galaxies of SDSSDR3, we can compare our identification procedure of ULIRGs and HLIRGs with that of Goto (2005). Firstly, we accept the correlation if a galaxy in SDSSDR4 lies within 3σ positional uncertainty ellipse of the IRAS source, while Goto (2003) treats a neighbouring optical galaxy as a match if the galaxy in SDSSDR3 lies within 20 arcsec of the IRAS source without regard to the IRAS error ellipse. This can cause many problems. For example,
SDSS J122907.3+020246 was identified as a HLIRG in Goto (2005). In Figure 2 we present the SDSS gri composite image of F12265+0219, which was regarded as the IRAS counterpart of SDSS J122907.3+020246 in Goto (2005). It is seen that SDSS J122907.3+020246 lies outside the 3σ error ellipse and a bright star-like object lies within the ellipse. The star-like object within the ellipse is the famous quasar 3C 273, which is known to be associated with F12265+0219. Since 3C 273 was not included in the spectroscopic targets of the SDSS and Goto (2005) used circular matching tolerance of 20 arcsec, the mismatch between F12265+0219 and SDSS J122907.3+020246 was included in his sample. Our cross-correlation based on the positional error ellipse, and the NED Near Position Search in step (v) of Section 2.2 help to avoid this kind of mismatching. Secondly, there is a difference in the calculation of infrared luminosity between Goto (2005) and this study. The former used the same function (2005) and this study. The former used the same function

\[
\text{LR} = \frac{N(<m)}{2\pi \sigma_1 \sigma_2 n(<m)}, \quad (1)
\]

where \(n(<m)\) is the local surface density of objects brighter than the candidate. The “normalised distance” \(r\) is given by

\[
r^2 = \left( \frac{d_1}{\sigma_1} \right)^2 + \left( \frac{d_2}{\sigma_2} \right)^2, \quad (2)
\]

where the \(d_1, d_2\) are the positional differences along the two axes of an error ellipse for an IRAS source, and \(\sigma_1, \sigma_2\) are the lengths of these axes. Since the positional uncertainties of galaxies in SDSS, 2dFGRS, and 6dFGS are negligible compared with those of IRAS sources, we define \(\sigma\) as the length of the error axes of the IRAS sources. \(Q(<m)\) is a multiplicative factor which is the a priori probability that a “true” optical counterpart brighter than the magnitude limit exists in the association, and for simplicity we set \(Q = 1\) in this study.

6 The quantities \(f_{12}, f_{25}, f_{60}, f_{100}\) represent the IRAS flux densities in Jy at 12μm, 25μm, 60μm, and 100μm, respectively.

7 We assume that a positional error of IRAS source is a Gaussian.

Figure 3. Reliability of our cross-correlation for SDSSDR4 (dotted line), 2dFGRSF (dashed line) and 6dFGSDR2 (solid line) as a function of LR. The vertical lines represent the critical LR values of reliable identification for each redshift survey data - above the critical LR values, the reliabilities are \(\geq 80\%\).

We compute \(n(<m)\) using photometric sample of galaxies within 3σ error ellipse,

\[
n(<m) = \frac{N(<m)}{9\pi \sigma_1 \sigma_2} \quad (3)
\]

where \(N(<m)\) represents the number of galaxies of which magnitudes are less than or equal to that of a candidate. We then obtain the likelihood ratio for our sample

\[
\text{LR} = \frac{9 \exp(-r^2/2)}{2N(<m)\quad (4)}
\]

We compute LR values for all 19,380 sources in the list of all matched sources of Section 2.1 using the photometric sample of galaxies in each redshift survey. In order to calculate the reliability of association using the LR values, we perform random associations by offsetting the IRAS source positions<br>by \(\approx 30\), and recompute LR values for each random association following Lonsdale et al. (1998) and Masci et al. (2001).

Using the distribution of LR values for true associations and random associations, the reliability of each association with a given LR is defined by

\[
R(LR) = 1 - \frac{N_{\text{random}}(LR)}{N_{\text{true}}(LR)}, \quad (5)
\]

where \(N_{\text{true}}(LR)\) and \(N_{\text{random}}(LR)\) are the number of true and random associations with a given LR. In Figure 3 we present the reliability of our cross-correlation for each redshift survey as a function of LR. Above log (LR) \(\sim -0.44\) (SDSSDR4), \(-0.39\) (2dFGRSDFR), \(-1.29\) (6dGSDR2), the reliabilities are \(\geq 80\%\). We show the LR distribution of our
There are three factors which make our sample incomplete. Firstly, since we used 3 $\sigma$ error ellipse for our cross-correlation, some ULIRGs outside 3 $\sigma$ error ellipse might be missed. If we assume an error ellipse to be a Gaussian distribution, the incompleteness originated from this term would be about 1 per cent. Secondly, some ULIRGs for which redshift qualities are unreliable (step (iv) in Section 2.2) are rejected, although their redshifts are not wrong. Thirdly, when more than two galaxies including a known optical counterpart galaxy are within the error ellipse of one IRAS source, the wrong galaxy may be selected as the optical counterpart of the IRAS source. In order to quantify the incompleteness introduced by those factors, we compute the ratio of ULIRGs that are surveyed in SDSSDR4, 2dFGRSDFRF and 6dFGSDR2 to those that are missed from our final sample of ULIRGs using previously known ULIRGs. Of the 636 known ULIRGs in Section 2.3 we consider only the 140 known ULIRGs that are expected to be found in this study. This sample consists of ULIRGs that are located within the redshift survey region and are found in FSC92. Additionally, their IR luminosities calculated using our method are greater than $10^{12}$ L$_\odot$. In the result of identification procedure in Section 2.1 and 2.2, 133 ULIRGs are found in our final sample of ULIRGs, and 7 ULIRGs are missed.

Of the 7 missed ULIRGs, three IRAS sources (F03202-0001, F14546+0338 and F22011+0017) have more than two galaxies including a known optical counterpart within their error ellipses. Our selection procedure is to choose the most likely counterpart (i.e. the galaxy with the larger value of LR), but this selects different galaxies to the known optical counterparts for these three IRAS sources. Therefore, the incompleteness introduced by our selection using LR values among several counterpart candidates is about 2.1 per cent (3 out of 140), although all the optical counterparts that we select are brighter or closer to the IRAS position than the known optical counterparts. In addition, one ULIRG (F09111-1007) is missed, because the optical counterpart in 6dFGSDR2 is outside 3 $\sigma$ error ellipse, and the association is already confirmed in the literature. Three ULIRGs (F00406–3127, F14485–2434, and F22123–2925) are missed because of their low redshift qualities as shown in Section 2.3. Although the redshifts quoted in the redshift surveys are same as those in the literature, therefore, the incompleteness introduced by our cross-correlation algorithm using 3 $\sigma$ error ellipse is about 0.7 per cent (1 out of 140), and the incompleteness introduced by our selection using the redshift quality parameter in the step (iv) of Section 2.2 is about 2.1 per cent (3 out of 140). In total, the incompleteness of the final sample of ULIRGs originated from this study is about 5 per cent (7 out of 140).

3 RESULTS

We have found 324 ULIRGs (126 in SDSSDR4, 27 in 2dFGRSDFRF, and 171 in 6dFGSDR2), 190 of which are newly discovered. We have therefore increased the number of known ULIRGs by about 30 per cent.

In Figure 5 we present the redshift distribution for the final sample of 324 ULIRGs identified in this study, and compare it to that of the 636 previously known ULIRGs. The redshifts in our final sample run from z=0.037 to z=0.517 and the median value is $\bar{z}=0.232$, which is larger than the median redshift $\bar{z}=0.184$ of the 636 previously known ULIRGs.

In Figure 6 we plot the IR luminosities of the ULIRGs identified in this study against their redshifts. In the upper and right panel, we present the redshift and luminosity distribution of ULIRGs found in each redshift survey, respectively. The ULIRGs identified in SDSSDR4 are found from low z to high z and from low luminosity to high luminosity.
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Figure 5. Redshift distribution of the 324 ULIRGs identified in this study (shaded region) compared to the 636 known ULIRGs (dashed lines), 134 known ULIRGs in the final sample in this study (filled region) and known ULIRGs plus all identified ULIRGs in this study (solid lines).

Figure 6. The IR luminosity of identified ULIRGs in this study versus redshift. The ULIRGs from the SDSSDR4, 2dFGRSDRF and 6dFGSDR2 are represented by squares, triangles, and pluses, respectively. In the upper and right panel, the redshift and luminosity distribution of ULIRGs found in each redshift survey are shown, respectively.

The luminosity distribution of the final sample is plotted in the Figure 7. For the final sample of ULIRGs (top panel), there are fewer ULIRGs at high luminosities than at low luminosities. The median luminosity value is $10^{12.17}L_\odot$.

Two interesting features are seen in the luminosity variation with redshift in Figure 7. Firstly, the number ratio of low luminous ULIRGs ($L_{ir} < 10^{12.2}L_\odot$) to all ULIRGs in redshift bin increases with redshift up to $z=0.25$ (due to the detection limit seen in Figure 6, there are few low luminous ULIRGs beyond $z=0.25$). Secondly, no ULIRGs that have IR luminosities of $\log (L_{ir}/L_\odot) > 12.50$ are found in the lower redshift ($z<0.25$). This is almost certainly due to the evolving luminosity function. A calculation of the evolving luminosity function is beyond the scope of this paper.

4 DISCUSSION

4.1 Comparison of ULIRG subsamples

Since we use three different redshift survey data to search for ULIRGs, different target selection functions in each redshift survey make our final sample of ULIRGs inhomogeneous. The majority of spectroscopic targets in each redshift survey are selected from magnitude limited samples. If we compare the luminosity distribution of the final sample with that of the SDSSDR4 (Figure 7), we find that the number of ULIRGs in SDSSDR4 is significantly lower than in the other two surveys. This may be due to the different selection criteria for spectroscopic targets (see each data release paper for more detail). Figure 7 shows that the upper envelope (shown by a dotted line) increases from $\log (L_{ir}/L_\odot) = 12.45$ to 12.95 as redshift increases. The lower envelope is due to the survey detection limit.

The primary sample of 6dFGS are galaxies with $K_{tot} < 12.75$ and one additional sample is optically selected galaxies with $bJ < 16.75$ (≈ 5%). Most spectroscopic targets of 2dFGRS are galaxies with $bJ < 19.45$, and the main galaxy sample...
but some additional spectroscopic targets are included depending on the redshift survey. In order to see the effects of the magnitude limit of each survey on our ULIRG sub-samples, we plot the absolute \( b_1 \) magnitude against redshift of ULIRG subsamples in Figure 8. A transformation from SDSS photometry to \( b_1 \) magnitude, and k-correction is done following Norberg et al. (2002). Since the majority of the spectroscopic targets in 6dFGS are \( K \)-band selected, most ULIRGs found in 6dFGS are fainter than the \( b_1 \) magnitude limit (\( b_1 = 16.75 \)) shown by the dotted line. The majority of ULIRGs found in 2dFGRS are above the magnitude limit (\( b_1 = 19.45 \)). The \( b_1 \) magnitude limit for the spectroscopic sample of SDSSDR4 is not clearly defined since the main spectroscopic sample of galaxies are Petrosian r-band selected sample. However, \( b_1 \) magnitude limit for the main galaxy sample of SDSSDR4 is similar to that of 2dFGRS, and most galaxies fainter than the \( b_1 \) magnitude limit are “Luminous Red Galaxies” (see Adelman-McCarthy et al. 2002 for more detail). It appears that a significant fraction (37%) of ULIRGs found in SDSSDR4 are fainter than the magnitude limit of 2dFGRS, implying that they are Luminous Red Galaxies.

In order to compare the infrared properties of our ULIRG subsamples associated with each redshift survey, we plot the infrared colour of log(ULIRG subsamples associated with each redshift survey, we implying that they are Luminous Red Galaxies. SDSSDR4 are fainter than the magnitude limit of 2dFGRS, and it appears that a significant fraction (37%) of ULIRGs found in SDSSDR4 are fainter than the magnitude limit of 2dFGRS, respectively. The dotted and dashed line indicate the \( b_1 \) magnitude limit of 6dFGS and 2dFGRS, respectively.

In conclusion, the sample of ULIRGs found in the three redshift surveys are not a simple magnitude limited sample due to the diverse target selection functions of each redshift survey.

4.2 Infrared Colours

Infrared colours such as log(\( f_{12} / f_{60} \)), log(\( f_{25} / f_{60} \)) and log(\( f_{60} / f_{100} \)) have long been used for classifying infrared sources. Infrared-bright stars have SEDs peaking typically around 12 \( \mu \)m, and can be distinguished from galaxies using the colour of log(\( f_{12} / f_{60} \)) (see, e.g., Cohen et al. 1987). In addition, log(\( f_{25} / f_{60} \)) has been used to classify ULIRGs into ‘Warm’ and ‘Cool’ systems. It has been suggested that ULIRG may evolve from ‘Cool’ system to ‘Warm’ system (Sanders et al. 1988; Veilleux, Kim & Sanders 2002). Soifer & Neugebauer (1991) showed that for luminous infrared galaxies including ULIRGs in the IRAS Bright Galaxy Survey, the mean log(\( f_{60} / f_{100} \)) colour increases with increasing IR luminosity.

We present the IR luminosity against infrared colour of log(\( f_{12} / f_{60} \)) in Figure 10 against log(\( f_{25} / f_{60} \)) in Figure 11 and against log(\( f_{60} / f_{100} \)) in Figure 12 for the final sample of 324 ULIRGs. The infrared-bright stars are known to have log(\( f_{12} / f_{60} \)) > 0 (see, e.g., Kim & Sanders 1998). All ULIRGs in the final sample have infrared colours of log(\( f_{12} / f_{60} \)) < 0.

In Figure 11 we plotted the boundary lines for the classification of normal galaxies, Seyfert 2 galaxies, and QSOs suggested by Neff & Hutchings (1992). If we restrict our attention to the ULIRGs with flux qualities of 2 or 3 (filled circles), the number ratio of these objects is N(Galaxy) : N(Sy2) : N(QSO) = 32 : 7 : 29. If we use the classification
Figure 10. The infrared luminosity against the infrared colour log\(\frac{f_{25}}{f_{60}}\) for the final sample of 324 ULIRGs in this study. The ULIRGs with flux upper limits at 12 \(\mu\)m are represented by open circles with arrows indicating the sense of the limit, and the ULIRGs with high or moderate flux qualities are represented by filled circles. The dotted line represents the boundary between galaxies and stars.

Figure 11. As Figure 10 except using the infrared colour log\(\frac{f_{25}}{f_{60}}\). The open circles and arrows represent the ULIRGs which have high or moderate flux qualities at 25 \(\mu\)m, and the filled circles denote the ULIRGs which have upper limits at 25 \(\mu\)m. The dotted lines represent the boundaries among normal galaxies, Seyfert 2 galaxies, and QSOs.

Figure 12. As Figure 10 except using the infrared colour log\(\frac{f_{60}}{f_{100}}\). The ULIRGs with flux upper limits at 100 \(\mu\)m are represented by open circles with arrows indicating the sense of the limit, and the ULIRGs with high or moderate flux qualities are represented as filled circles. The open squares are at the mean colour and the central luminosity of ULIRGs in the three luminosity bins (12.0 \(\leq\) log\(\frac{L_{ir}}{L_\odot}\) < 12.3, 12.3 \(\leq\) log\(\frac{L_{ir}}{L_\odot}\) < 12.6, and 12.6 \(\leq\) log\(\frac{L_{ir}}{L_\odot}\) < 12.9). The vertical errorbars define the limiting luminosities of the bins, and the horizontal errorbars represent standard deviation of log\(\frac{f_{60}}{f_{100}}\) colours in each bin. The dotted line represents the selection criteria (log\(\frac{f_{60}}{f_{100}}\) > −0.3) of 1 Jy sample of ULIRGs [Kim & Sanders 1998].

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scheme of ‘Warm’ ULIRGs \(\left(f_{25}/f_{60} > 0.2\right)\) or log\(\frac{f_{25}}{f_{60}}\) > −0.7) and ‘Cool’ ULIRGs \(\left(f_{25}/f_{60} < 0.2\right)\) or log\(\frac{f_{25}}{f_{60}}\) < −0.7) suggested by [Sanders et al. 1988], the number ratio for the sample becomes N(Cool) : N(Warm) = 38 : 30. This ratio is much smaller than that of 1 Jy sample (N(Cool) : N(Warm) = 90 : 25, [Kim & Sanders 1998]. This difference might be related to the different selection criteria for ULIRGs, but is likely to be strongly affected by the exclusion of ULIRGs which have upper limit flux at 25\(\mu\)m.

In Figure 12 the log\(\frac{f_{60}}{f_{100}}\) colours of ULIRGs with flux quality of 2 or 3, range from −0.80 to +0.22 and have a mean of −0.19. This mean value is low compared to those of other ULIRG samples (see, e.g., [Kim & Sanders 1998] and references therein). In addition, 21 per cent (42 out of 203) of ULIRGs with flux quality of 2 or 3, have colours of log\(\frac{f_{60}}{f_{100}}\) less than −0.3, while no ULIRGs in 1 Jy sample have colours of log\(\frac{f_{60}}{f_{100}}\) less than −0.3 due to their selection criteria (log\(\frac{f_{60}}{f_{100}}\) > −0.3) of ULIRGs [Kim & Sanders 1998]. We plotted the mean colours in each luminosity bin by open squares to investigate any dependence of the colour on the IR luminosity. It appears that there are no significant IR luminosity dependence of log\(\frac{f_{60}}{f_{100}}\) in our sample (up to \(10^{12.6} L_\odot\)), though our colours are still warmer than those typical in less IR-luminous galaxies.

We compare the IR luminosity and the redshift distribution of ULIRGs with flux qualities of 1 (open circles in
Figure [11][12] to those with flux qualities of 2 or 3 (filled circles). The mean IR luminosity for ULIRGs with flux qualities of 1 at 12 \( \mu m \) is not different from that for ULIRGs with flux qualities of 2 or 3 as seen in Figure [10]. Similar results are found for ULIRGs at 25 \( \mu m \) and at 100 \( \mu m \). The median redshift (\( z=0.230 \)) for ULIRGs with flux qualities of 1 at 12 \( \mu m \) is larger than that (\( z=0.163 \)) for ULIRGs with flux qualities of 2 or 3 at 12 \( \mu m \). Similarly, the median redshifts for ULIRGs with flux qualities of 1 at 25 \( \mu m \) (\( z=0.236 \)) and at 100 \( \mu m \) (\( z=0.262 \)) are larger than those for ULIRGs with flux qualities of 2 or 3 at 25 \( \mu m \) (\( z=0.148 \)) and at 100 \( \mu m \) (\( z=0.196 \)).

4.3 Hyperluminous Infrared Galaxies

Of the 14 HLIRG candidates satisfying selection criteria of HLIRGs up to step (iii) in Section 2.2, all were excluded in further steps. However, we identified two HLIRGs, F01044--4050 and F09105+4108, in the course of NED Near Position Search for ULIRGs candidates at step (v) in Section 2.2. We list the 2 HLIRGs identified in this study in Table 5. Column (1) lists the IRAS object name in the FSC92. Columns (2) and (3) list the J2000.0 source position. Column (4), (5), (6) and (7) give the IRAS flux densities and their errors at 12\( \mu m \), 25\( \mu m \), 60\( \mu m \) and 100\( \mu m \), respectively. The IRAS flux density at each band is given in Column (8). Column (9) lists the finally accepted redshift and Column (10) gives the IR luminosity calculated in this study. Log (LR) is given in the final Column. In Figure 13 we present 3' \times 3' greyscale images and contour plots extracted from the SuperCOSMOS scans of \( f_p \) survey plates (left panel), as well as those from the SDSS gri composite image and the SDSS r-band image (right panel) for the final sample of two HLIRGs. The identification procedure and properties of the HLIRGs are given in Appendix B of the electronic issue.

5 SUMMARY

We present a new sample of ULIRGs and HLIRGs found by cross-correlating the IRAS sources in FSC92 with the spectroscopic samples of galaxies in the SDSSDR4, 2dFGRSDRF and 6dFGSDR2. Our primary results are summarised below:

(i) We have identified 324 ULIRGs including 190 newly discovered ULIRGs in the regions of the sky covered by the SDSSDR4, 2dFGRSDRF and 6dFGSDR2. We increase the number of catalogued ULIRGs by about 30 per cent.

(ii) The reliability of the cross-correlation is estimated using the likelihood ratio method. We compute the likelihood ratio of each association for our sample of ULIRGs. The completeness of the final sample has been estimated using previously known ULIRGs in the redshift surveyed region. The incompleteness introduced by our identification procedure due to the cross-correlation using 3 \( \sigma \) error ellipse, and the selection using LR value and using the redshift quality parameter is estimated to be about 5 per cent.

(iii) The redshifts in our final sample run from \( z=0.037 \) to \( z=0.517 \) and the median value is \( z=0.223 \), which is larger than that (\( z=0.184 \)) in previous ULIRG samples.

(iv) Two HLIRGs, F01044--4050 and F09105+4108, are found in the course of NED Near Position Search of ULIRGs candidates.

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Table 5. The Final Sample of HLIRGs

| FSC NAME | RA (J2000) | Dec (J2000) | 12µm (Jy) | 25µm (Jy) | 60µm (Jy) | 100µm (Jy) | Flux Qual | log L_{IR} | log(LR) |
|----------|------------|-------------|-----------|-----------|-----------|-----------|----------|-----------|--------|
| F01044-4050 | 01 06 44.9 | -40 34 21 | 0.140(0.042) | 0.155(0.039) | 0.405(0.049) | 0.655(0.203) | 1231 | 0.584 | 13.19 | 0.648 |
| F09105+4108 | 09 13 44.0 | 40 56 34 | 0.129(0.031) | 0.333(0.033) | 0.525(0.042) | 0.437(0.109) | 2331 | 0.442 | 12.97 | 0.191 |

Figure 13. Similar to the Figure 1, except for two HLIRGs, F01044–4050 (left two panels) and F09105+4108 (right two panels), identified in this study. The small circle in the first panel indicate the position of 6dF J0106412−403437.
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