THE FIRST SAMPLE OF ULTRALUMINOUS INFRARED GALAXIES AT HIGH REDSHIFT.
I. SAMPLE AND NEAR-INFRARED MORPHOLOGIES

S. A. STANFORD
Physics Department, University of California at Davis, and the Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratories, Livermore, CA 94550; adam@igpp.ucllnl.org

DANIEL STERN
Department of Astronomy, University of California, Berkeley, CA 94720; dan@bigz.berkeley.edu

WIL VAN BREGEL
Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratories, Livermore, CA 94550; wil@igpp.ucllnl.org

AND

CARLOS DE BREUCK
Leiden Observatory, and Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratories, Livermore, CA 94550; debreuck@igpp.ucllnl.org

Received 2000 May 12; accepted 2000 June 9

ABSTRACT

We present a new sample of distant ultraluminous infrared galaxies. The sample was selected from a positional cross-correlation of the IRAS Faint Source Catalog with the FIRST database. Objects from this set were selected for spectroscopy by virtue of following the well-known star-forming galaxy correlation between 1.4 GHz and 60 μm flux, and by being optically faint on the POSS. Optical identification and spectroscopy were obtained for 108 targets at the Lick Observatory 3m telescope. Most objects show spectra typical of starburst galaxies and do not show the high-ionization lines of active galactic nuclei. The redshift distribution covers 0.1 < z < 0.9, with 13 objects at z > 0.5 and an average redshift of z = 0.31. K-band images were obtained at the IRTF, Lick, and Keck observatories in sub-arcsec seeing of all optically identified targets. About two-thirds of the objects appear to be interacting galaxies, while the other one-third appear to be normal. Nearly all the identified objects have far-IR luminosities greater than 10^{11} \ L_\odot, and \sim 25\% have L_{FIR} > 10^{12} \ L_\odot.

Subject headings: galaxies: interactions — galaxies: starburst — infrared: galaxies — radio continuum: galaxies

On-line material: machine-readable table

1. INTRODUCTION

Observations by the Infrared Astronomy Satellite (IRAS) led to the discovery of a class of galaxies with enormous far-IR luminosities. Subsequent observations over a large range of wavelengths have shown that these objects, called ULIGs for ultraluminous infrared galaxies, have (1) bolometric luminosities and space densities comparable to those of optical quasars (Sanders et al. 1988); (2) a broad range in host galaxy spectral type, including starburst galaxies, Seyfert I and II, radio galaxies, and quasars; (3) morphologies often suggestive of recent interactions or merging (Carico et al. 1990; Leech et al. 1994; Rigopoulou et al. 1999); and (4) large amounts of molecular gas concentrated in small (< 1 kpc) central regions (e.g., Scoville et al. 1989; Solomon et al. 1997). Understanding the nature of the prime energy source in ULIGs has proven difficult (e.g., Smith, Lonsdale, & Lonsdale 1998). Many of the observed characteristics indicate that very strong starbursts could be the culprit. Alternatively, an active galactic nucleus (AGN) may power the ULIG (e.g., Lonsdale, Smith, & Lonsdale 1993). The very high luminosities suggest an evolutionary connection between ULIGs and quasars, wherein a dust-shrouded central massive black hole is gradually revealed as the appearance of the object changes from ULIG to quasar (Sanders et al. 1988).

Much effort has been expended in trying to determine the primary source of energy—starbursts or AGNs—driving the large FIR luminosities. The recent studies using ISO indicate that the vast majority of the power comes from starbursts in \sim 80\% of the observed systems (Genzel et al. 1998; Lutz et al. 1998). Rigopoulou et al. (1999) present the results of an expanded version of the mid-IR spectroscopic survey first reported by Genzel et al. (1998). Using ISO to observe 62 ULIGs at z < 0.3, they measured the line to continuum ratio of the 7.7 μm polycyclic aromatic hydrocarbon (PAH) feature to differentiate between starburst and AGN as the dominant source of the large FIR luminosity. PAH features have been shown to be strong in starburst galaxies and weak in AGNs (Moorwood 1986; Roche et al. 1991). Rigopoulou et al. confirmed the results of Genzel et al. (1998), and also found, based on near-IR imaging, that approximately two-thirds of their sample have double nuclei and nearly all the objects show signs of interactions. For a recent review of ULIGs see Sanders & Mirabel (1996).

ULIGs are also of great interest for studies of early star formation in the building of galaxies. Recent sub-mm observations suggest that objects similar to ULIGs may contain a significant fraction of the star formation at high redshifts (e.g., Lilly et al. 1999). But so far most studies have found ULIGs only in the nearby universe. Sanders et al. (1988) initially studied a group of 10 objects at z < 0.1. Previously published systematic surveys have found objects mostly at
z < 0.4 (Leech et al. 1994; Clements et al. 1996a, 1996b). A few high redshifts objects have been found, all of which turn out to contain hidden AGNs. These include FSC 15307+3252 at $z = 0.926$ (Cutri et al. 1994) and FSC 10214+4724 at $z = 2.286$ (Rowan-Robinson et al. 1991). The former object was found to exhibit a highly polarized continuum, indicating the presence of a buried quasar (Hines et al. 1995), while the latter was found to be lensed (Eisenhardt et al. 1996) and also shows signs of containing a hidden AGN (Lawrence et al. 1993; Elston et al. 1994; Goodrich et al. 1996). Further progress in this field has been hampered by the lack of identified ULIGs at moderately high redshifts.

No new deep far-IR survey will become available prior to the launch of SIRTF, which will be capable of studying ULIGs in detail at high redshifts. So, the IRAS database remains the primary source of targets for finding high-redshift ULIGs. Radio observations provide a relatively unbiased method for extracting FIR galaxies from the IRAS Faint Source Catalog (Moshir et al. 1992, hereafter FSC) because radio continuum emission is relatively unaffected by extinction in dense gas and dust. Such FIR/radio samples are ideal for detailed investigations of the complex relationships between the interstellar media, starbursts, and possible AGNs in ULIGs. For example, a sample of radio-loud objects was constructed by cross-correlating the IRAS FSC with the Texas 365 MHz radio catalog (TXFS; Dey & van Breugel 1990). Subsequent optical identifications and spectroscopy showed that the TXFS objects tend to be distant AGNs. So a radio-quiet sample, extracted from the FSC, should be an excellent means of finding ULIGs without AGNs—i.e., powered by starbursts—at interesting cosmological distances. In this paper, we report on such a sample: we describe the sample selection process and discuss the near-IR imaging. We defer a detailed analysis of the radio properties and optical spectroscopy to future papers.

2. THE FIRST/FSC SAMPLE

We have used two large area surveys in the radio and far-IR, which we briefly describe here, to select ULIG candidates. In the radio, we have used the FIRST (Faint

![Plot of $F_\nu$ at 1.4 GHz against $F_\nu$ at 60 $\mu$m showing all matches of the positional cross-correlation of FIRST with the IRAS FSC (solid triangles), along with several comparison samples taken from the literature. The well-known radio–FIR correlation for star-forming galaxies extends to the faintest flux limits probed by the FF objects.](image-url)
Images of the Radio Sky at Twenty cm; Becker, White, & Helfand 1995). Using the VLA, this project is surveying π steradians down to a 5 σ limit of 1 mJy with 5″ resolution and subarcsec positional accuracy. One of the problems with finding distant ULIGs using IRAS is that there are many faint galaxies visible in a deep optical image within the relatively large error ellipse of an FIR source. The high resolution and good positional information of FIRST offer an excellent means of choosing the best of the many optical candidates on which to spend valuable large telescope time getting redshifts. We used the second version of the catalog (released 1995 October 16), which samples 2925 deg² in two regions of sky in the north (7°20′< R.A.(J2000)< 17°20′, 22°2< decl.(J2000)< 42°5) and south (21°20′< R.A.(J2000)< 3°20′, −2°5< decl.(J2000)< 1°6) Galactic Caps. In the far-IR we have used the IRAS FSC, which resulted from the Faint Source Survey (FSS). Relative to the IRAS Point Source Catalog, the FSS achieved better sensitivity by point-source filtering the detector data streams and then co-adding those data before finding sources. At 60 μm (the band used for defining our candidates), the FSC covers the sky at |b| ≥ 10°10 and has a reliability (integrated over all signal-to-noise ratios) of ≥ 94%. The limiting 60 μm flux density of the FSC is approximately 0.2 Jy, where the signal-to-noise ratio (SNR) is ∼5. The FSS also resulted in the Faint Source Reject file which contains extracted sources not in the FSC with an SNR above 3.0. We used the FSR, in addition to the FSC, with part of FIRST to increase the number of targets in the fall sky.

The IRAS FSC was positionally cross-correlated with the second version of the FIRST catalog, with the requirements that an FSC source must have a real 60 μm detection (J_{60 μm} ≥ 1) and that it be within 60° of the FIRST source. The 60 μm band was chosen because it is more reliable than the 100 μm band and samples close to the wavelength peak of the ULIG power. The resulting FIRST-FSC (FF) catalog contains 2328 matches. To increase the available objects in the fall sky, we also performed a positional match of the FSR with the South Galactic Cap portion of FIRST, which yielded an additional 176 matches. The 20 cm and 60 μm flux densities for this sample of 2504 sources are plotted in Figure 1. The majority of the FF sources fall along the well-known radio-FIR correlation (Condon et al. 1991), extending from nearby starburst galaxies to much fainter FIR/radio flux levels. The surface density of such objects is approximately 1 deg^{-2} down to the ∼5 σ limits of 1 mJy at 20 cm and ∼0.2 Jy at 60 μm.

We generated optical finding charts using the Digitized Sky Surveys, available from the Space Telescope Science Institute, for all 2504 matches. The radio source position and the FSC error ellipse were overlaid on these charts. Visual inspection of these finding charts was carried out to select optically faint targets for further study, with the expectation that such targets would be distant ULIGs. Approximately 150 targets, which will carry the designation FF along with the usual coordinate naming scheme, were selected in this manner. A strict cutoff in optical magnitude was not employed, and we make no attempt to construct a sample which has a well-defined limiting magnitude in the optical. In practice, the magnitude of the targets selected for optical imaging and spectroscopy depended on the observing conditions, i.e., some targets which are not visually faint on the DSS image were observed during cloudy conditions. While the FIRST and FSC catalogs do have well-defined flux limits, our sample was not constructed in order to be complete to a chosen flux level in either the radio nor the far-IR bands. The main goal of the survey is simply to find high-redshift ULIGs. It is worth noting that our target list would include objects with observed characteristics in the radio, optical, and far-IR similar to those of FSC 10214+4724 (which itself lies outside of the FIRST area that we used and so cannot fall into our catalog). We have not found any ULIGs at redshifts as great as that of FSC 10214+4724 in the ~3000 deg² surveyed.

3. OBSERVATIONS

During several runs from 1996 March to 1999 April, the Kast spectrograph (Miller & Stone 1994) at the Shane 3 m telescope of Lick Observatory was used to obtain optical images and spectroscopy of the candidate ULIGs from our FF catalog. The observing procedure typically consisted of taking two 300 s images in the r_s band, identifying the optical counterpart of the FF source in these data, and immediately following up with slit spectroscopy of the optical object. Because the resolution and positional accuracy of FIRST are high, it was usually clear which optical object coincided with the radio source. The FWHM of the seeing in the images was usually in the range 1′.5–2′0. Standard stars were observed in imaging mode when conditions were photometric. However, because much of the data were obtained during nonphotometric conditions, r_s magnitudes will not be presented here for the sample. Unless the source morphology demanded a particular value, the position angle of the slit was set to the parallactic angle. The object was dithered along the slit by ∼10′ between two exposures to aid in fringe subtraction. Optical spectra of 1200–6000 s duration were obtained of the optical source using the 300 line mm^{-1} grating in the red-side spectrograph, which provides ∼4.6 Å pixel^{-1} resolution from 5070 to 10590 Å, and a 452/3306 grism in the blue-side spectrograph which provides ∼2.5 Å pixel^{-1} resolution from 3000 to 5900 Å. The slit width was set at 2′. The images and spectra were reduced using standard techniques.

Near-infrared images were obtained of the targets for which redshifts had been determined in order to better ascertain the morphologies of the galaxies. K’ images were obtained for nearly all identified targets with NSFCAM at the IRTF 3 m telescope in 1998 August and 1999 February. Additional observations of three targets were obtained in service mode in 1999 September. NSFCAM was used in its 0’3 pixel^{-1} mode which provides a 77” × 77” field. Typical total exposure times per object were 960 s; more distant objects were observed for twice this period. Conditions were photometric with seeing averaging 0’9. Observations of standard stars from the Persson et al. (1998) list were obtained and used to calibrate the images onto the California Institute of Technology (CIT) system, which is defined in Elias et al. (1982). The data were reduced using standard techniques.

Five targets were observed in the K band using Gemini (McLean et al. 1993) at the Shane 3 m telescope on 1998 October 7. Gemini has 0.68 pixels which give it a 174” field. Objects were observed for 1080 s each in photometric conditions with seeing of ∼1′2. The data were reduced using standard techniques and calibrated onto the CIT system using observations of UKIRT faint source standards (Casali & Hawarden 1992).
Two distant targets were imaged at the Keck I telescope with NIRC (Matthews & Soifer 1994) in 1998 April. FF1106 + 3201 was observed in the $K$ band for 16 minutes, and FF1614 + 3234 was observed for 32 minutes in the $K_s$ band. Both objects were observed in clear conditions with $\sim 0.5$ seeing. These data were reduced using standard techniques and calibrated onto the CIT system using observations of UKIRT faint source standards (Casali & Hawarden 1992).

4. RESULTS

4.1. Optical

We attempted spectroscopic observations of approximately 150 $IRAS$/FIRST candidates, of which 116 yielded redshift information. The 108 with infrared imaging are listed in Table 1; the eight sources with redshifts but lacking infrared images are not considered further. The sources which did not provide useful spectra were usually observed in poor conditions; the reasons for their lack of redshifts were not their intrinsically challenging spectra. The object names in Table 1 are based on the FIRST radio position. The source in the FIRST catalog would have the name given by the object’s coordinates shown in our Table 1, in the format FIRST Jhhmmss.s +ddmmss, where the coordinates are truncated, not rounded. In the $IRAS$ FSC, the FIR source name is different from that implied by our FF name, so we have included the FSC source name as a column in Table 1. The $Z$ designation in the FSC name means that the FIR source is from the FSR catalog.

The typical resolution of the spectroscopy was $\approx 15$ Å (FWHM) at $\lambda > 5500$ Å, implying typical uncertainties of $\leq 0.002$ in redshift. Redshifts were determined from the spectra after identifying probable emission lines and continuum features. In practice the features most often used were the $[\text{O~II}]$ $\lambda 3727$, $[\text{O~III}]$ $\lambda\lambda 4959, 5007$, and $H_\alpha$ lines, and the D4000 break. The vast majority of the spectra have the emission lines characteristic of star formation; very few show any signs, such as high-ionization lines, of an AGN. Four sample spectra, covering a range in redshift, signal-to-noise, and spectral type, are shown in Figure 2. A more detailed analysis of the optical spectra is deferred to a later paper.

4.2. Near-Infrared

The $K'$ images are displayed for each object, along with the optical finding chart from the DSS, in Figure 3. Photometry of the FF objects was obtained from the $K'$ images. In Table 1, the $K$ magnitudes within 3" diameter apertures, centered on the peak of the near-IR emission, are given for each object. The 5 $\sigma$ detection limit in most of the images is $K \sim 19$ so the limiting factor in the uncertainty of the photometry is not the signal-to-noise, since most objects have magnitudes some 3–4 mag brighter than the detection limit,
| Source     | R.A. (J2000) | Decl. (J2000) | K*   | S_0(100 nm) | S_0(0.44) | log L_21 cm | z     | (μm)  | 20 cm Morphology | 20 cm Morphology |
|------------|--------------|---------------|------|-------------|------------|-------------|-------|-------|-----------------|-----------------|
| FF 0001    | 00 14 45.16  | +01 41 37.06  | 0.278| 15.6        | 0.16       | 0.24p       | 10.1  | 10.1  | 2 lobes         | Two nuclei      |
| FF 0010    | 00 17 52.09  | +02 42 44.77  | 0.320| 15.0        | 0.23       | 0.39        | 11.04 | 11.73 | Complex         | Extended        |
| FF 0011    | 00 17 52.09  | +02 42 44.77  | 0.320| 15.0        | 0.23       | 0.39        | 11.04 | 11.73 | Complex         | Extended        |
| FF 0012    | 00 17 52.09  | +02 42 44.77  | 0.320| 15.0        | 0.23       | 0.39        | 11.04 | 11.73 | Complex         | Extended        |
| FF 0013    | 00 17 52.09  | +02 42 44.77  | 0.301| 15.0        | 0.23       | 0.39        | 11.04 | 11.73 | Complex         | Extended        |

**Notes:**
- "2 lobes" indicates two lobes in the morphology.
- "Two nuclei" indicates two nuclei with a gap.
- "Extended" indicates extended morphology with no specific sub-type mentioned.
- "Complex" indicates a complex morphology, possibly with multiple components.
- "Point" indicates a point-like source with no extended structure.
- "Interacting pair" indicates two interacting sources.
- "Merger" indicates a merging event.
- "Disturbed" indicates a disturbed morphology, possibly due to recent interactions.
- "Tidal tail" indicates a tidal tail morphology.
| Source | FSC | RA (J2000) | Dec (J2000) | z | K* | S_K (mag) | S_20cm (mJy) | Morphology |
|-------|-----|------------|-------------|---|----|-----------|--------------|-------------|
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| FF 0850+3925 | 08 58 14.496 | 09 37 52.644 | 33 57 16.01 | 0.26 | 11.69 | 0.37 | Extended |
| Source       | FSC      | R.A. (J2000) | Decl. (J2000) | $z$  | $K^a$ (mag) | $S_{60 \mu m}$ (Jy) | $S_{100 \mu m}$ (Jy) | log $L_{\text{FIR}}$ ($L_\odot$) | $S_{1.4 \text{GHz}}$ (mJy) | 20 cm Morphology | K-Band Morphology |
|--------------|----------|--------------|---------------|------|-------------|---------------------|---------------------|-------------------------------|------------------|-----------------|-------------------|
| FF 1726 + 3656 ...... | F17252 + 3659 | 17 26 57.757 | +36 56 39.45 | 0.365 | 16.0 | 0.30 | 0.35 | 12.23 | 1.67 | Double? | Disturbed |
| FF 2119 + 0007 ...... | Z21169 −0005 | 21 19 32.215 | +00 07 44.43 | 0.289 | 14.8 | 0.15 | 0.16 | 11.69 | 3.55 | Point | Interacting pair |
| FF 2122 − 0000 ...... | F21198 −0013 | 21 22 20.646 | −00 00 46.41 | 0.297 | 15.4 | 0.19 | (0.41) | 11.93 | 0.75 | Point | Tidal tail |
| FF 2131 − 0141 ...... | Z21293 −0154 | 21 31 53.490 | −01 41 43.35 | 0.730 | 19.7 | 0.19 | 0.56 | 12.90 | 2.79 | Complex | Faint |
| FF 2136 − 0112 ...... | F21340 −0125 | 21 36 34.229 | −01 12 08.38 | 0.21 | 16.2 | 0.33 | 1.12 | 11.95 | 3.20 | Point | Normal with companion |
| FF 2136 − 0019 ...... | F21341 −0033 | 21 36 46.011 | −00 19 47.06 | 0.210 | 15.6 | 0.32 | (0.40) | 11.73 | 1.24 | Extended | Two nuclei |
| FF 2000 − 0038 ...... | F21581 −0053 | 22 00 47.250 | −00 38 48.08 | 0.356 | 16.1 | 0.35 | (0.40) | 12.27 | 28.9 | Extended | Tidal tails |
| FF 2200 + 0108 ...... | Z21583 +0054 | 22 00 51.859 | +01 08 27.08 | 0.164 | 14.7 | 0.23 | 0.72 | 11.53 | 2.82 | Extended | Normal with companion |
| FF 2216 + 0058 ...... | F22134 +0043 | 22 16 02.721 | +00 58 10.65 | 0.212 | 16.5 | 0.46 | 0.72 | 11.93 | 1.31 | Point | Asymmetric |
| FF 2221 − 0042 ...... | Z22188 −0058 | 22 21 26.066 | −00 42 39.08 | 0.189 | 17.3 | 0.26 | 1.00 | 11.77 | 0.66 | Point | Faint |
| FF 2330 − 0025 ...... | F23279 −0041 | 23 30 34.920 | −00 25 03.98 | 0.252 | 15.8 | 0.19 | 0.62 | 11.86 | 1.65 | Extended | Tidal tails |
| FF 2331 − 0000 ...... | Z23283 −0017 | 23 30 54.903 | −00 00 40.12 | 0.173 | 15.3 | 0.16 | (0.54) | 11.44 | 2.68 | Extended | Disturbed with companion |
| FF 2331 − 0143 ...... | Z23292 −0159 | 23 31 50.519 | −01 43 05.97 | 0.228 | 14.9 | 0.20 | 0.42 | 11.69 | 1.40 | Extended | Interacting |
| FF 2341 − 0201 ...... | F23390 −0217 | 23 41 36.151 | −02 01 06.44 | 0.174 | 15.9 | 0.32 | 0.57 | 11.59 | 1.20 | Point | Interacting |
| FF 2341 + 0016 ...... | F23392 +0000 | 23 41 48.137 | +00 16 55.06 | 0.331 | 16.0 | 0.23 | 0.38 | 12.07 | 1.43 | Extended | Interacting |
| FF 2352 − 0015 ...... | Z23503 −0032 | 23 52 53.171 | −00 15 24.69 | 0.227 | 15.3 | 0.19 | 0.57 | 11.74 | 0.59 | Point | Interacting |

**Note.** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

- $^a$ K-band magnitudes were measured through a 3.0 diameter aperture.
- $^b$ 100 $\mu$m fluxes shown in parentheses are upper limits.
- $^c$ K-band data obtained with NIRC at Keck I.
FIG. 3. For each of the FF objects in Table 1 we show on the left the DSS finding chart centered on the FIRST radio position, which is marked by a small circle of diameter 5 arcsec, with the FSC 95% confidence limit error ellipse superposed. The astrometric uncertainty between the optical and radio reference frames is ~ 1 arcsec. On the right in each panel is a close-up view of the K-band image of the identified source. North is up and east to the left in all panels.
FIG. 3. Continued

FF0138+0031, z = 0.148

DSS

K-band

FF0139+0115, z = 0.612

DSS

K-band

FF0123+0114, z = 0.089

DSS

K-band

FF0111-0123, z = 0.154

DSS

K-band
Continued

Fig. 3. Continued
Fig. 3.—Continued
Fig. 3.—Continued
FIG. 3. Continued.

FF0814+3030, z = 0.124

K-band

DSS

FF0816+3101, z = 0.407

K-band

DSS

FF0822+3030, z = 0.148

K-band

DSS

FF0804+3919, z = 0.164

K-band

DSS
FIG. 3. Continued

FF0823+3202, z = 0.396

K-band

DSS

FF0826+3042, z = 0.248

K-band

DSS

FF0817+3125, z = 0.359

K-band

DSS

FF0822+3726, z = 0.263

K-band

DSS
Fig. 3. Continued

FF0835+3559, z = 0.201

K-band

DSS

FF0835+3257, z = 0.288

K-band

DSS

FF0835+3708, z = 0.357

K-band

DSS

FF0852+3502, z = 0.190

K-band

DSS
FIG. 3. Continued

K-band

FF0856+3450, z = 0.220

DSS

FF0858+3925, z = 0.228

DSS

FF0807+3931, z = 0.224

DSS

FF0903+3630, z = 0.289

K-band

Continued
FIG. 3. Continued

FF0945 + 2939, z = 0.274

K-band

DSS

FF0947 + 4026, z = 0.219

K-band

DSS

FF0937 + 3857, z = 0.621

K-band

DSS

FF0944 + 3100, z = 0.261

K-band

DSS
Fig. 3.—Continued
Fig. 3.—Continued
Fig. 3. Continued

K-band

FF1200+3004, z = 0.224

DSS

FF1223+3339, z = 0.263

DSS

K-band

FF1115+3045, z = 0.152

DSS

K-band

FF1124+3836, z = 0.294

DSS
Continued
FF1251+3211, z=0.326

DSS           K-band

FF1421+3726, z=0.291

DSS           K-band

FF1412+3014, z=0.257

DSS           K-band

FF1429+3957, z=0.388

DSS           K-band

Fig. 3.—Continued
Fig. 3—Continued
FIG. 3—Continued

FF1532+3242, z = 0.926

FF1540+3758, z = 0.183

FF1514+3629, z = 0.338

FF1520+3013, z = 0.254

DSS

K-band

DSS

K-band

DSS

K-band
Fig. 3.—Continued
Fig. 3. Continued

FF1713+3843, $z = 0.171$

K-band

DSS

FF1725+3709, $z = 0.689$

K-band

DSS

FF1659+3549, $z = 0.371$

K-band

DSS

FF1707+3725, $z = 0.311$

K-band

DSS
Fig. 3. Continued

FF1726+3656, z = 0.365

FF2122-0000, z = 0.297

FF2131-0141, z = 0.730

FF2119+0007, z = 0.289
Fig. 3. Continued
Fig. 3. Continued
but rather systematics in the zero point. We estimate that the uncertainty in the zero point is 0.03 mag. For most objects the 3" diameter aperture contains \( \sim 70\% \) of the total light. The morphologies of the objects tend to show signs of galaxy interactions, including tidal tails, multiple nuclei, and disturbed outer envelopes. Approximately two-thirds of the sample show such features, while one-third of the sample appear to be normal galaxies. A brief description of the near-IR morphology for each FF is included in Table 1.

### 4.3. Radio

One of the major advantages of using FIRST in our survey is the high accuracy of its positional information. The coordinates listed in Table 1 are those of the radio source as given by the FIRST catalog, which has an absolute astrometric uncertainty of \( \sim 1" \). The 20 cm VLA images of all objects listed in Table 1 were extracted from the FIRST database. The radio morphologies were classified by visual inspection of these cutout images and by consulting the deconvolved sizes listed in the FIRST catalog. The 20 cm morphological information is given for each FF source in Table 1. The 20 cm flux densities listed in Table 1 have typical uncertainties of 10\% at the 2 mJy level.

### 4.4. Far-Infrared

Improved \( IRAS \) flux densities were obtained for all objects in Table 1 with the ADDSCAN utility at IPAC. In addition to the 60 \( \mu \)m band used to construct our FF catalog, data at 12, 25, and 100 \( \mu \)m was searched for detections. Almost none of the objects in Table 1 were detected at either of the shorter two wavelengths, so no information is included from these wavebands in Table 1. Many detections were obtained in the 100 \( \mu \)m data; these are included where available in Table 1, and 1 \( \sigma \) upper limits are indicated in parentheses. The uncertainty in the typical 60 \( \mu \)m measurement in the sample is \( \sim 10\% \), and \( \sim 15\% \) in the 100 \( \mu \)m band where detected. The 60 and 100 \( \mu \)m flux densities were used to calculate the far-infrared luminosity, as defined by
Sanders & Mirabel (1996): \[ L(40-500 \, \mu m) = 4\pi D_L^2 CF_{\text{FIR}}[L_\odot], \] where \( D_L \) is the luminosity distance in Mpc, \( F_{\text{FIR}} = 1.26 \times 10^{-14}(2.58 \times f_{60} + f_{100})[\text{W m}^{-2}] \), and \( C = 1.6 \). Throughout this paper we use \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( \Omega_M = 0.3 \) with \( \Lambda = 0 \). When 100 \( \mu m \) detections could not be obtained with ADDSCAN, the 1 \( \sigma \) limiting flux densities were used in the calculation of the \( L_{\text{FIR}} \). The \( L_{\text{FIR}} \) are given in Table 1 and are plotted in Figure 4. The uncertainty in the \( L_{\text{FIR}} \) is dominated by a combination of the typical \( \sim 10\%-15\% \) flux measurement errors and the \( \sim 15\% \) uncertainty in the scaling factor \( C \), which accounts for the extrapolated flux longward of the 100 \( \mu m \) band.

5. DISCUSSION

The reliability of the optical identification with the radio source for the objects in Table 1 is very high. The optical/radio source association with the FSC far-infrared source is less certain, because of the relatively large positional uncertainty of the \( \text{IRAS} \) detections. But there are at least four reasons to believe that the identified optical/radio sources are indeed the FSC sources as well. First, in all cases, the FIRST position is within twice the 1 \( \sigma \) error ellipse of the FSC source. Second, the optical spectra show emission lines typical of star-forming galaxies, as expected for most far-IR luminous objects. Third, in the cases where both 60 and 100 \( \mu m \) detections were obtained, the \( \text{IRAS} \) flux ratios are typical of FIR luminous galaxies (Soifer et al. 1987). Finally, in nearly all cases the FIR/radio flux ratio lies on the well-established correlation as seen in Figure 1.

There are at least two possible ways that the wrong association is being made. First, a galaxy optically brighter than the identified FF source could lie just outside the \( \text{IRAS} \) error ellipse and still be the source of the \( \text{IRAS} \) detection. But in our sample there are no such galaxies which are also detected by FIRST, as would be expected if such objects were the true source of the FIR emission. Second, a faint radio source could be missed by the FIRST survey that would coincide with the FSC source. Using the rms given in the FIRST catalog for each object, lower limits to the resulting \( S_{60\mu m}/S_{20\text{cm}} \) ratios for objects beneath the FIRST detection limits are found to be \( \sim 500-700 \), far greater than the standard ratio for star-forming galaxies. Finally, it is worth noting that on average one expects to find only 0.035 FIRST sources within the typical \( \text{IRAS} \) error ellipse area, so the probability of a random radio source being associated with an FSC source is low. In our sample of 108 identified FF objects, approximately four could be due to radio sources unassociated with the far-IR source.

Although we defer the scientific analysis of the new sample to future contributions, we will briefly compare some basic global properties of our FF sample to those of other similarly large samples of high-redshift ULIGs which have been previously published, e.g., Leech et al. (1994) and Clements et al. (1996a, 1996b). Our new sample has ULIGs at higher average redshift (\( \bar{z} \sim 0.3 \)) than that of Leech et al. (\( \bar{z} \sim 0.17 \)) and that of Clements et al. (\( \bar{z} \sim 0.21 \)). As for the interaction rate, on which there has been some disagreement in the literature (Sanders & Mirabel 1996), our result that two-thirds of the sample shows signs of galaxy interactions is in agreement with Leech et al. but not Clements et al., who found that \( \sim 90\% \) of their sample were interacting systems. Finally, the rate of AGN-type optical spectra in our sample, which is only 10\%, is somewhat less than the \( \sim 25\% \) found by Clements et al. We do see a higher incidence of AGN-type spectra at the highest \( L_{\text{FIR}} \) as has been noted previously by several studies; for a review of this topic see Sanders & Mirabel (1996).

6. SUMMARY

We have constructed a new survey of ULIGs using a match of the \( \text{IRAS} \) FSC with the second version of the FIRST catalog, which covered nearly 3000 deg\(^2\). By choosing for further study only optically faint matches from the DSS which also fall on the radio-FIR flux correlation, we have attempted to find high-redshift ULIGs which are powered primarily by starbursts. Optical images and spectra were obtained of 108 such targets, which were found to lie in the redshift range 0.1 < \( z < 0.9 \); a redshift histogram is shown in Figure 5. Nearly all of these targets have \( L_{\text{FIR}} \) greater than \( 10^{11} \, L_\odot \) and have a higher average redshift of \( \bar{z} = 0.31 \) than in other recent ULIG surveys. Near-infrared imaging shows that while more than the majority of objects show clear signs of galaxy interactions, nearly one-third appear to be normal at arcsec resolution in the \( K \) band. With this sample, we intend to examine the nature of ULIG evolution in future contributions.

The authors thank the staff of Lick Observatory for their help in obtaining the optical data, and Bill Vacca and Dave Griep at the IRTF for their assistance in obtaining the near-IR data, and for conducting servicing observing for three of the sample objects. We have made use of the on-line facilities provided by IPAC. We also thank Bob Becker for providing us with the FIRST catalog and for help in using its contents. Finally, we thank Rob Kennicutt for a speedy referee report. The Digitized Sky Surveys were produced at the Space Telescope Science Institute under US Government grant NAG-W-2166. The images of these surveys are based on photographic data obtained using the Oschin...
Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the compressed digital form with permission of these institutions. The work by S. A. S., W. v. B., and C. D. B. at IGPP/LLNL was performed under the auspices of the US Department of Energy under contract W-7405-ENG-48 to the University of California. The work by D. S. was supported by IGPP grants 98-AP017 and 99-AP026.

REFERENCES

Becker, R. White, R., & Helfand, D. 1995, ApJ, 450, 559
Carico, D., Graham, J. R., Matthews, K., Wilson, T. D., Soifer, B. T., Neugebauer, G., & Sanders, D. B. 1990, ApJ, 349, L39
Casali, M., & Hawarden, T. 1992, JCMT-UKIRT Newslett., 4, 33
Clements, D., Sutherland, W. J., McMahon, R. G., & Saunders, W. 1996a, MNRAS, 279, 477
Clements, D., Sutherland, W. J., Saunders, W., Efstathiou, G. P., McMahon, R. G., Maddox, S., Lawrence, A., & Rowan-Robinson, M. 1996b, MNRAS, 279, 459
Condon, J. J., Anderson, M. L., & Helou, G. 1991, ApJ, 378, 65
Cutri, R. M., Huchra, J. P., Low, F. J., Brown, R. L., & vanden Bout, P. A. 1994, ApJ, 424, L65
Dey, A., van Breugel, W., & Shields, J. C. 1990, in IAU Colloq. 124, Paired and Interacting Galaxies, ed. J. Sulentic, W. C. Keel, & C. M. T. Telesco (Huntsville: NASA), 309
Eisenhardt, P. R., Armus, L., Hogg, D. W., Soifer, B. T., Neugebauer, G., & Werner, M. 1996, ApJ, 461, 72
Elias, J. H., Frogel, J. A., Matthews, K., & Neugebauer, G. 1982, AJ, 87, 1029
Elston, R., McCarthy, P. G., Eisenhardt, P., Dickinson, M., Spinrad, H., Januzzi, B. T., & Maloney, P. 1994, AJ, 107, 910
Genzel, R., et al. 1998, ApJ, 498, 579
Goodrich, R. W., Miller, J. S., Martel, A., Cohen, M. H., Tran, H. D., Ogle, P. M., & Vermeulen, R. C. 1996, ApJ, 456, L9
Hines, D. C., Schmidt, G. D., Smith, P. S., Cutri, R. M., & Low, F. J. 1995, ApJ, 450, L1
Lawrence, A., et al. 1993, MNRAS, 260, 281
Leech, K. J., Rowan-Robinson, M., Lawrence, A., & Hughes, J. D. 1994, MNRAS, 267, 253
Lilly, S. J., Eales, S. A., Gear, W. K. P., Hammer, F., Le Fevre, O., Crampston, D., Bond, J. R., & Dunne, L. 1999, ApJ, 518, 641
Lonsdale, C., Smith, H., & Lonsdale, C. 1993, ApJ, 405, L9
Lutz, D., Spoon, H. W. W., Rigopoulou, D., Moorwood, A. F. M., & Genzel, R. 1998, ApJ, 505, 103
Matthews, K., & Soifer, B. T. 1994, Exp. Astron, 3, 77
McLean, I. S., et al. 1993, Proc. SPIE, 1946, 513
Miller, J. S., & Stone, R. P. S. 1994, Lick Obs. Tech. Rep. 66
Moorwood, A. F. M. 1986, A&A, 166, 4
Moshir, M., et al. 1992, Explanatory Supplement to the IRAS Faint Source Survey, version 2, JPL D-10015 8/92 (Pasadena: JPL)
Persson, S. E., Murphy, D. C., Krzeminski, W., Roth, M., & Rieke, M. J. 1998, AJ, 116, 2475
Rigopoulou, D., Spoon, H. W. W., Genzel, R., Lutz, D., Moorwood, A. F. M., & Tran, Q. D. 1999, AJ, 118, 2625
Roche, P. F., Aitken, D. K., Smith, C. H., & Ward, M. J. 1991, MNRAS, 248, 606
Rowan-Robinson, M., et al. 1991, Nature, 351, 719
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988, ApJ, 325, 74
Scoville, N. Z., Sanders, D. B., Sargent, A. I., Soifer, B. T., & Tinney, C. G. 1989, ApJ, 345, L25
Smith, H. E., Lonsdale, C. J., & Lonsdale, C. J. 1998, ApJ, 492, 137
Soifer, B. T., Sanders, D. B., Madore, B. F., Neugebauer, G., Danielson, G. E., Elias, J. H., Lonsdale, C. J., & Rice, W. L. 1987, ApJ, 320, 238
Solomon, P. M., Downes, D., Radford, S. J. E., & Barrett, J. W. 1997, ApJ, 487, 144