THE STRUCTURE OF INFRARED-LUMINOUS GALAXIES AT 100 MICRONS
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ABSTRACT
We have observed 22 galaxies at 100 μm with the Kuiper Airborne Observatory in order to determine the angular size of their FIR-emitting regions. This one-dimensional array data constitutes the highest spatial resolution ever achieved on luminous galaxies in the far-infrared. Most of these galaxies are very luminous far-infrared sources, with \( L_{\text{FIR}} > 10^{11} L_\odot \). We clearly resolved six of these galaxies at 100 μm and have some evidence for extension in seven others. Those galaxies that we have resolved can have little of their 100 μm flux directly emitted by a pointlike active galactic nucleus. Dust heated to \(~ 40 \text{ K}\) by recent bursts of nonnuclear star formation provides the best explanation for their extreme FIR luminosity. In a few cases, heating of an extended region by a compact central source is also a plausible option.
Subject headings: galaxies: active — galaxies: starburst — infrared: galaxies

1. INTRODUCTION
Data from the Kuiper Airborne Observatory (KAO), and later the Infra-Red Astronomical Satellite (IRAS) revealed that many galaxies emit much more flux in the far-infrared (FIR; \(~ 40–120 \text{ μm}\) than in any other wavelength band (Telesco & Harper 1980; Houck et al. 1984; Soifer et al. 1984; de Jong et al. 1984). This FIR emission is usually attributed to thermal emission from warm (\(~ 40 \text{ K}\)) dust heated by starbursts (Elston, Cornell, & Lebofsky 1985; Lawrence et al. 1986). There may also be a direct non-thermal contribution to the FIR luminosity from an active galactic nucleus (AGN), but at least the energy distributions suggest that emission from warm dust grains likely dominates the FIR flux even if there is an obvious active core and the galaxy is not obviously dusty (Barvainis, Antonucci, & Coleman 1992; Chini 1992; Soifer, Houck, & Neugebauer 1987; Edelson & Malkan 1987).

While the most likely scenario for the FIR emission in galaxies is dust absorbing strong radiation from a burst of young massive stars, other scenarios are possible. Extended dust could also be heated directly by an AGN core. In addition, the dust could be reprocessing less energetic photons from an older population of stars in the galaxy, an energy source that is known to dominate in relatively low luminosity quiescent systems (cf. Helou 1986; Persson & Helou 1987). It has been suggested that the dust could be heated by hot (10⁸ K) intergalactic gas (Dwek & Arendt 1992; Bregman, McNamara, & O’Connell 1990), but this would happen only when such hot gas exists in the vicinity, as in the center of a large cluster of galaxies. Dust could also be heated by shocks in the interstellar medium during the collision or interaction of galaxies (Harwit et al. 1987).

Each of the dust-heating mechanisms above should correspond to particular spatial distributions of FIR light. If the FIR emission is from the active core itself, the flux should appear pointlike. If it is from dust heated by an active nucleus, one might expect color temperature gradients to point toward the nucleus. Starburst-heated dust should have about the same scale size as the burst itself because the young stars are well mixed with the gas from which the stars are forming and the optical depth for their UV photons is very high in the interstellar medium. On the other hand, dust heated by nonionizing photons from a cooler population of stars that expel condensables might be expected to follow the smooth distribution of older stars in the galaxy. It is well understood that evidence for interactions, collisions, and mergers is almost invariably associated with the most luminous infrared galaxies, and comparison of the far-infrared luminosity distribution with that of the interaction geometry is a vital clue to the mechanism by which this energy is produced.

The question that motivated this observational project was a straightforward one. Does the far-infrared emission in luminous galaxies, representing the bulk of the emitted energy, show any evidence for spatial structure using the highest angular resolutions that are available to us? The distribution of luminosity in these sources can be a key to understanding their energy production mechanisms. Our observations address this question, and relevant observational strategies are developed for future high-resolution studies. An associated question is whether these measurements can be used to help distinguish between the various plausible heating mechanisms.

High angular resolution observations in the far-infrared are seriously handicapped compared with observations in most other spectral regions. This part of the spectrum, containing the peak of energy emission from luminous galaxies, is inaccessible from the ground, and the angular resolution that can be achieved is completely diffraction limited. A large aperture above the terrestrial water vapor absorption is a necessary tool. While large ground-based telescopes can attack the problem on arcsecond scales using tracers of hot and cool dust in the mid-IR and submillimeter continuum respectively, the correspondence of this dust with the distribution of warm dust that dominates the energy budget of luminous galaxies is not completely understood. To date, the largest telescopes that routinely observe in this spectral region are airborne and balloon-borne facilities.

While its high sensitivity allowed it to catalog many sources, IRAS resolved only the largest and nearest galaxies because of its comparatively large beam size of \(~ 2^\prime–4^\prime\) at 60 and 100 μm. Deconvolution efforts improved on this resolution somewhat but could not approach the \(~ 23^\prime\) diffraction-limited beam of the KAO. While Infrared Space Observatory (ISO) too has made fine contributions to the study of luminous galaxies, the higher signal-to-noise (S/N)
the di†raction-limited beam size of that telescope; for example, with ISOPHOT could not o†set the substantially larger ratios that could be achieved in the far-infrared continuum with ISOPHOT could not offset the substantially larger di†raction-limited resolution at this wavelength. This With its 0.9 m aperture, the KAO allowed the highest pos-
determination of the grain temperatures from the spectral color temperatures, which can be signiÐcantly different in sources with substantial optical depth.

In § 2 the sample of galaxies that we observed is discussed. Section 3 will cover details about the observations, and § 4 will describe the analysis methodology. Section 5 presents the general results from this study, along with a discussion for each galaxy. Further discussion of the results follows in § 6.

2. THE SAMPLE

Our sample consisted of 22 galaxies with IRAS 100 μm fluxes greater than or equal to 8 Jy. Their targeting coordi-

| Galaxy       | R.A. (1950) | Decl. (1950) | References | Date (mm/dd/yy) | Rot.* | Calib.* |
|--------------|-------------|--------------|------------|-----------------|-------|---------|
| MCG +02-04-025 | 01:17:23.17 | +14:05:58.8 | 1          | 06/01/94        | 0     | CEK     |
| III Zw 35    | 01:41:47.90 | +16:51:06.3 | 2          | 29/08/9         | 3.9   | IS      |
| UGC 02369    | 02:51:15.9  | +14:46:03   | 3          | 29/08/9         | 1.4   | IS      |
| NGC 1275     | 03:16:29.5  | +41:19:52.2 | 4          | 06/01/94        | 18.5  | CEK     |
| VII Zw 31    | 05:08:17.5  | +79:36:40   | 5          | 12/08/99, 16/08/94 | 15.2  | Pal.    |
| UGC 05101    | 09:32:04.78 | +61:34:37.0 | 3          | 06/01/94        | 0     | CEK     |
| NGC 3110     | 10:01:32.0  | -06:13:56   | 1          | 06/01/94        | 4.6   | CEK     |
| NGC 4151     | 12:08:01.06 | +39:41:02   | 6          | 06/01/94        | 6.0   | CEK     |
| UGC 08696    | 13:42:51.71 | +56:08:14.3 | 3          | 26/08/95        | 6.5   | IM      |
| NGC 6090     | 16:10:24.58 | +52:35:05.4 | 3          | 12/08/94, 16/08/94 | 9.7   | Pal.    |
| NGC 6286     | 16:57:44.99 | +59:00:41.7 | 3          | 16/08/94        | 7.2   | Pal.    |
| IRAS 1713+53 | 17:13:14.14 | +53:13:49.3 | 1          | 26/08/95, 29/08/95 | 18.7  | IM, IS  |
| IRAS 1720−00 | 17:20:07.8  | -00:14:15.9 | 7          | 26/08/95        | 0     | IM      |
| UGC 10923    | 17:36:23.6  | +86:46:38   | 8          | 26/08/95, 29/08/95 | 14.7  | IM, IS  |
| NGC 7469     | 23:00:44.41 | +08:36:15.8 | 3          | 16/08/94        | 0     | Pal.    |
| NGC 7541     | 23:12:11.2  | +04:15:41   | 1          | 12/08/94        | 4.2   | Pal.    |
| Zw 475.056   | 23:13:33.1  | +25:17:01.6 | 3          | 29/08/95        | 6.3   | IS      |
| NGC 7625     | 23:18:00.0  | +16:57:07   | 1          | 16/08/94        | 0     | Pal.    |
| NGC 7770     | 23:48:49.9  | +19:49:13   | 1          | 26/08/95        | 3.3   | IM      |
| NGC 7771     | 23:48:52.1  | +19:50:01   | 1          | 26/08/95        | 2.1   | IM      |
| Mrk 331      | 23:48:54.1a | +20:18:28.8 | 3          | 29/08/95        | 4.4   | IS      |
| UGC 12915    | 23:59:08.3  | +23:13:00.0 | 9          | 26/08/95d       | 3.9   | IM      |

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

* Angle in degrees over which the array rotated during the observations.

b Calibrator source. CEK: 1 Ceres, 52 Europa, and 97 Klotho average; Pal: 2 Pallas; IM: 704 Interamnia and 56 Melete average; IS: 704 Interamnia and 386 Siegena average.

c This is the pointing position. The CHYT position is actually 23:48:54.03.

d UGC 12915 also was observed on 1994 Aug 16; values given in the tables are for the 1995 Aug observation (see § 5.2.21)

References.—(1) Condon et al. 1990 (CHSS); (2) Chapman et al. 1990; (3) Condon et al. 1991b (CHYT); (4) Harrington et al. 1983; (5) Sage & Solomon 1987; (6) Wilson & Ulvestad 1982; (7) Martin et al. 1989; (8) Kojoian, Elliot, & Biacay 1981; (9) Condon et al. 1993.
nates and the dates on which they were observed are listed in Table 1. The peak radio position of each galaxy was used for targeting because radio positions are more accurately known than the optical or FIR positions and are likely to correspond closely to the FIR peak (Bicay & Helou 1990). All of the galaxies except NGC 4151 (see also below) and UGC 10923 are part of the Revised Bright Galaxy Sample (BGS) (Soifer et al. 1989) or the Bright Galaxy Survey—Part II (BGS2) (Sanders et al. 1995).

The vagaries of airborne astronomy flight planning led to a somewhat inhomogeneous mix of objects. In general, the brightest sources possible were attempted, and so while the sample includes a wide range of luminosities our observations were intentionally biased toward the highest. All of the sources except NGC 4151 and NGC 7625 have $L_{\text{FIR}} > 10^{10} L_\odot$ and 14 have $L_{\text{FIR}} > 10^{11} L_\odot$. Physical characteristics of the sample galaxies are listed in Table 2. NGC 4151 is by far the least luminous galaxy observed with a $\log(L_{\text{FIR}}/L_\odot) = 9.5$ and was included in the sample specifically to confirm an earlier detection of extended emission (Engargiola et al. 1988; Gaffney et al. 1992). As it turns out, it provides an excellent contrasting case to the others.

An additional selection constraint came from our attempt to select galaxies with relatively bright guide stars nearby. This was required because the galaxy core was rarely bright enough to lock onto with the KAO optical guider. Because of this selection criterion, most of the galaxies are within $7'$ of an object with a magnitude $V < 12$ as listed in the Hubble Telescope Guide Star Catalog (GSC). However, the GSC does not list only stars, and several of the objects that we had planned to use as guide stars turned out to be brighter galaxies themselves. So by preferentially choosing galaxies with nearby bright GSC objects, 16 of our 22 galaxies turned out to have obvious nearby companion galaxies. The ratio of FIR luminous galaxies with companions to those without, in an unbiased sample, is between 1:4 and 1:8 (Soifer et al. 1984), so even for our luminous galaxy sample, our ratio of greater than 2:3 implies a significant bias toward galaxies with companions.

Other subtleties of airborne astronomy had a strong influence on the particular galaxies used in our sample but not their characteristics (aside from the bias noted above). The telescope in the airplane is essentially immobile in the azimuth direction, so pointing in azimuth is accomplished by flying the airplane in the proper direction. The azimuth of the object being observed thus determines the direction of flight. The challenge of piecing together observing legs on relevant objects (such that one can eventually return to home base) and the need to observe the largest number of objects determined the time and azimuth at which each object was observed. Since the instrument was not equipped with an image rotator, the position angle of our linear array across each galaxy was not independently selectable, and the array remained oriented approximately in elevation. For sources in which a particular position angle was strongly preferred, this position angle became a flight planning constraint that sometimes could be achieved by observing at the right parallactic angle.

| Galaxy | Distance (Mpc) | $L_{\text{FIR}}/L_\odot$ | $S_{\text{1.4 GHz}}$ (mJy) | Radio References | $q^c$ | Type | Type References |
|--------|----------------|--------------------------|-----------------------------|----------------|------|------|----------------|
| MCG +02-04-025... | 123 | 11.3 | 49.1 | 1 | 2.32 | H II | 6, 7 |
| III Zw 35........ | 108 | 11.3 | 41.2 | 1 | 2.56 | AGN | 7 |
| UGC 02369........ | 123 | 11.3 | 50.0 | 1 | 2.32 | H II | 7 |
| NGC 1275.......... | 68 | 10.7 | 24,000d | 2 | −0.44 | AGN | 8 |
| VII Zw 31......... | 218 | 11.6 | 41.6 | 2 | 2.28 | H II | 9 |
| UGC 05101.......... | 164 | 11.8 | 150.0 | 1 | 2.10 | AGN | 7, 10 |
| NGC 3110........... | 66 | 10.9 | 109.0 | 1 | 2.22 | H II | 7 |
| NGC 4151........... | 17 | 9.5 | 332.0 | 1 | 2.27 | AGN | 12 |
| NGC 0696........... | 157 | 11.9 | 143.0 | 1 | 2.27 | AGN | 6, 7 |
| NGC 6080.......... | 122 | 11.2 | 46.4 | 1 | 2.01 | H II, AGN | 6, 7 |
| NGC 6286........... | 80 | 11.0 | 142.0 | 1 | 2.51 | H II | 7 |
| IRAS 1713+53........ | 208 | 11.6 | 25.8 | 1 | 2.33 | H II | 7 |
| IRAS 1720−00........ | 174 | 11.9 | 102.0 | 2 | 2.19 | ... | ... |
| UGC 10923........... | 103 | 11.0 | 48.2 | 4 | 2.33 | AGN | 7, 8 |
| NGC 7469........... | 66 | 11.3 | 169.0 | 1 | 2.32 | AGN | 7 |
| NGC 7541........... | 35 | 10.7 | 150.0 | 1 | 2.53 | AGN | 7 |
| Zw 475.056......... | 110 | 11.2 | 142.0 | 1 | 2.32 | H II | 11 |
| NGC 7625........... | 23 | 9.9 | 42.0 | 1 | 2.37 | H II | 7 |
| NGC 7770........... | 58 | 10.2 | 16.5 | 1 | 2.39 | H II | 7 |
| NGC 7771........... | 58 | 11.0 | 107.3 | 1 | 2.51 | H II | 7 |
| Markarian 331....... | 72 | 11.1 | 67.6 | 1 | 2.51 | H II | 7 |
| UGC 12915.......... | 61 | 10.6 | 47.0 | 5 | 2.19 | ... | ... |

* This assumes $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and is corrected for Virgocentric infall. Taken from references (1) and (2) except for NGC 4151 from Hunt & Giovanardi 1992 and UGC 10923 from Mazzaralla et al. 1994.

b Using distance in second column and FIR flux (see eq. [3], § 5.1.2) appropriate for the radio flux given in the fourth column.

c See eq. (2) in text.

d Variable

References.—(1) CHSS; (2) Condon et al. 1996; (3) Condon 1987; (4) Marx et al. 1994; (5) Condon et al. 1993; (6) Lonsdale et al. 1993; (7) Veilleux et al. 1995; (8) Seyfert 1943; (9) Djorgovski et al. 1990; (10) Sanders et al. 1988; (11) Giuricin et al. 1994; (12) Li et al. 1993; (13) Bernlohr 1993.
3. OBSERVATIONS

All galaxies and calibration sources were observed with the 0.9 m Kuiper Airborne Observatory (KAO) flying from Moffett Field, CA. Data presented in this paper is from flights on 1994 January 6, August 12, and August 16 and on 1995 August 26 and 29. The University of Texas $2 \times 10^3$ He-cooled silicon bolometer array was used with a filter centered near 100 $\mu$m. See Harvey (1979) for details of the “100 $\mu$m narrow” filter responsibility for this instrument.

The detectors in the $2 \times 10$ spatial array are rectangular in shape with the short sides of the detectors aligned along the long axis of the array. The long dimension of each detector corresponds approximately to the size of the diffraction spot of the KAO at 100 $\mu$m ($\lambda/D \sim 23$). The short dimension of each detector is half as large and thus critically samples the diffraction spot. The detectors have center-to-center separation of 13.8” along the long axis of the array and 28” between the two arms (see Fig. 1) giving relatively little dead space between elements. Each detector has a FWHM beam size of 30” x 40” with the short axis aligned along the length of the array. This is the same array and identical beam sizes to those that were used in the observations of Smith & Harvey (1996).

The data were taken in the nodding mode, as in Smith & Harvey above, alternating the position of the source between the two beams created by the ~4’ azimuth chop (along the short axis of the array). The detectors were systematically over bright point sources during each flight series in order to determine individual detector responsivities for flat fielding. These detector-to-detector responsivity ratios vary by about 5% for different point sources on the same flight (Smith et al. 1994) and by a similar amount for point sources between flights during the same flight series. This is far less than the photometric uncertainties from other parts of our calibration (see §4.1).

The telescope was targeted so that the peak of the FIR emission, which was presumed to correspond to the radio emission, which was presumed to correspond to the radio, was on the center of the middle detector on one of the arms of the array (detector 5; see Fig. 1 for definition of detector numbers and coordinates). Only for NGC 4151 was the visual core bright enough that direct guiding using the KAO focal plane video camera was possible.

The second arm of the array (detectors 11–20) was of lower quality, with several nonfunctional elements and others with high noise. As a result, the source was centered on the first arm (1–10) and used data from this second arm mostly as a check on positioning. The data from this second arm of the detector array are not presented here, though the locations of that second arm are shown in the figures to present the auxiliary information that was available.

Since it was usually not possible to guide on the galaxy itself, guiding was done on a nearby offset star. On telescopes with an altitude-azimuth mount such as the KAO, the field of view rotates while tracking. When offset guiding, this means the FIR source will appear to revolve around the guide star. Only by knowing the field rotation can the array be accurately targeted at the FIR source. This angle is only known to ~0.3 on the KAO because of the limited resolution of the telescope stabilization system. So the best pointing is achieved by using guide stars that are close to the galaxy, where the uncertainty in the field rotation will result in the smallest possible offset from the galaxy to the array center. Guide stars less than 10’ away from the galaxy were used consistently so the resulting tracking uncertainty was less than 3’. This is a small fraction of the size of the pixels. The guide star positions were taken from the GSC, which can be assumed to be reliable at this level or better.

On the 1994 August 16 flight as well as the 1995 flights, the 100 $\mu$m boresight was either poorly defined on the array or the boresight drifted during the flight. The result of the poor boresight is that the center of the peaks shifted from the center of detector 5 by as much as 7’. The effects of the shifts and how they were dealt with will be discussed in §4.1.

4. DATA REDUCTION

The images in Figures 2–23 show the detector array projected on the digitized Palomar Observatory Sky Survey (DSS) image with detector 5 centered at the position for each galaxy given in Table 1 (our target position), rotated to the average position angle at which it was observed. The range of the position angles over which the array moved during the time of observation is listed in Table 1, but for simplicity this is not shown on the figures. The change in position angles was usually fairly small, but in some cases was as much as 20° over the course of our observation. Since the effect of this field rotation is to rotate the array around the target center, the outermost detectors (1 and 10) could have been, at times, as far as 12” from the positions shown in the figures. Usually the position angle changed by far less and in some cases the KAO “freeze mode” was used, which rotated the whole telescope at the same rate as the sky rotated so that the range in position angle was limited only by the telescope rotation stability (about 0.3’). This was possible only for tracks in which the field rotated by less than the ±2’ dynamic range of the telescope line-of-sight axis.

4.1. Flux Calibration

Careful flux calibration might not seem necessary in view of the fact that we are mainly trying to determine the angular size and shape of the object. Nevertheless, good
determinations of the emission of the galaxy in the relatively small beam combined with the larger beam observations from IRAS provided an additional test for extension. If we get less signal in our peak detector than a point source with the cataloged IRAS flux should produce, we could interpret the deficit as evidence for extension on a scale of the detector size.

In order to make these comparisons worthwhile, it must be the case that the flux determinations are firmly on the IRAS photometric system. The IRAS 100 $\mu$m primary standards were, however, all substantially resolved in our small beam, making them difficult to use as point-source comparisons. Therefore, we developed a secondary system of standards using asteroids, which are pointlike for both instruments. The utility of such a system of standards has been recognized for ISOPHOT calibration (e.g., Muller & Lagerros 1998).

In summary, this calibration effort involved using the radiometric constants derived from the IRAS Minor Planet Survey (Tedesco 1992) (which give identically the IRAS fluxes for the relevant orbital geometry at the IRAS observation epoch) and used these radiometric constants to calculate their brightness at the particular epoch of our observations. The asteroids are thus used as roving standards, where the thermophysical characteristics are taken as the calibration constants, and the predicted flux densities vary in a predictable way with the distances to the Sun and to Earth.

Our choice of asteroids was constrained by those that were bright enough to give a high signal-to-noise ratio detection and those that were targetable in terms of the flight planning constraints detailed above. In addition, asteroids were rejected from our sample that were known to show more than 10% optical variability, which, whether because of albedo variations or nonsphericity, might cause similar variations and predictive uncertainties at 100 $\mu$m.

Temperatures and fluxes of these asteroids were calculated with a simple thermal model (Lebofsky et al. 1986). The model assumes (1) spherical shapes, so that the flux does not vary with rotation; (2) slow rates of rotation, so that the dark side of the asteroid has time to cool down completely and only the sunlit side radiates in the IR; (3) albedos that are uniform and equal to those used in the IRAS Asteroid Survey; (4) sizes from the IRAS asteroid survey; and (5) thermal equilibrium for all points on the asteroid. An uncertainty of 10% is appropriate to the asteroid fluxes calculated with this model. Deriving the system responsivities from the observed signal corrected for our filter response and the calculated asteroid fluxes puts us on the IRAS photometric system and allows comparisons between our fluxes and the fluxes from IRAS.

On 1994 January 6, 1 Ceres, 52 Europa, and 97 Klotho were observed in order to calibrate the galaxy fluxes. We failed to observe an asteroid on 1994 August 12 and had to use the observation of 2 Pallas performed on August 16 to calibrate. In spite of this, we have confidence in the stability of the system responsivity because of the repeatability of the galaxy signal strengths on different nights. For NGC 7541, which was observed only on August 12, the calculated flux density matches the IRAS flux. The data were calibrated with 704 Interamnia and 56 Melete on the 1995 August 26 flight and with 704 Interamnia and 386 Siegena on the 1995 August 29 flight.

In addition to asteroids, IRC +10420 was observed as a point-source calibrator and to define the boresight. IRC +10420 cannot be used for photometry because it seems to vary at 100 $\mu$m from as low as 177 $\pm$ 30 Jy to as high as 360 $\pm$ 108 Jy (Harvey 1991) and in the optical and near-infrared as well (Jones et al. 1993). We also could not compare our observations of this object made on the flights of August 12 and 16 to make up for the lack of a calibrating asteroid observation on the August 12 flight. A problem with the secondary chopping mirror that started after we observed IRC +10420 on August 12 and before any galaxies were observed changed the system sensitivity and prevents any simple comparison of IRC +10420 signals from the two nights. The same chopping problem existed on the entire August 16 flight.

A one-dimensional FIR profile was obtained for each galaxy and calibrator source by plotting the signal in each of the detectors 1–10. These plots are shown in Figures 2–23. To these profiles a baseline was fitted to the end detectors. The baseline was usually the best-fit line through detectors 1, 2, 9, and 10. While the baseline allowed us to subtract small offsets that are the residual from chopping and nodding, that subtraction makes the derived fluxes entirely insensitive to emission on scales greater than $\sim$100$''$ in the direction along the long axis of the array. Optical images of each galaxy suggest that there is not likely to be a great deal of emission on scales larger than 100$''$ scales unless the galaxy is very close. The small/large beam flux comparison provides a check on this assumption.

For each asteroid, the contributions from detectors 1–10 were then added up, divided by the calculated flux of the asteroids, and divided the result by a factor 0.96 (which corrects our filter response to that of the IRAS bandpass) to get the system responsivity (signal per IRAS unit jansky) at 100 $\mu$m for detectors 1–10. The same thing was done for the signal observed only in detector 5 to derive a measurement with a smaller effective aperture. See Table 3 for the actual signal levels (in DN) and responsivities for each of the asteroids. For flights with more than one asteroid observation, the average responsivity derived from all asteroids observed was used. The signal uncertainties for the asteroids include not only that due to noise from each of the detectors but also that associated with the uncertainty of the placement of the baseline. These contribute approximately equally to the total uncertainty quoted.

Because of the stability of the system from flight to flight, we might have expected the total system responsivities shown in the last two columns of Table 3 to be the same. The varying responsivities listed for the various flights differ because of changes in the system configuration between the flights and in particular the chopping problem experienced in 1995 August.

The profiles of some asteroids and galaxies were not exactly centered in detector 5 of the detector array owing to boresight shifts. In order to compensate for such small pointing errors, a Gaussian profile was fitted to each of the high S/N point-source profiles of IRC +10420 obtained on the August flights and to the pointlike 1 Ceres profile for the 1994 January flight. The shift along the array needed to fit the point-source Gaussian (with the same signal in detectors 1–10 as the galaxy or asteroid profile) to the two detectors in each source profile with the highest signal (usually detectors 4 and 5) was calculated. Since most sources had profiles that differed only slightly from that of a point source, the fit
told us how far the center of the diffraction spot was from detector 5 along the long axis of the array as well as the signal that each detector should have had if the source had been perfectly centered.

The galaxy flux density was calculated by taking the signal from the galaxy and multiplying by the responsivity from the asteroids. This was then corrected for the response of the galaxy to the filter by dividing the result by a factor 0.87. This is a different factor than for the asteroids because of the much cooler spectral shape of the galaxies. Fluxes for the galaxies calculated from the signal in the central detector 5 only, corrected for any mispointing, are shown in the first column of Table 4. The detector 5 flux is simply the signal from that detector translated into the equivalent flux of a point source centered on detector 5. The detector 5 flux should always be less than or equal to that summed across the whole array (detectors 1–10, also shown), but uncertainties (mostly in baseline removal) allow some galaxies in Table 4 to have center detector fluxes slightly larger than their summed flux. As noted above, the uncertainties for all fluxes include not only include that associated with the individual detectors but also include some attempt to estimate the uncertainty associated with removing the baselines. Uncertainty from the asteroid calibration (assumed to be 10%) is also included in the totals quoted. Our error bars do not include small additional contributions from stratospheric opacity variations, filter corrections, and mispointing, but these contributions are not a significant source of uncertainty. It can be seen from the point-source profiles in Figure 2 that the uncertainties in offset guiding targeting discussed above should have only a minor effect on the signal that was measured. The effect of pointing errors on the measured source profile is discussed in more detail below.

In spite of the many steps and possible pitfalls in this calibration, it is gratifying that, within the uncertainty, the measured galaxy fluxes never exceed the IRAS fluxes, which is consistent with a calibration of high accuracy.

Our observed small-beam fluxes are compared to the large-beam IRAS fluxes of these galaxies at 100 μm in the BGS (Soifer et al. 1989) and the BGS2 (Sanders et al. 1995). For dust at 30–50 K with emissivity exponent \( n = 1–2 \), color correction changes the IRAS fluxes at 100 μm by only about 5%. This is insignificant compared to the much larger uncertainty (\( ~15\%-20\% \)) of our calibration, so we do not correct the IRAS fluxes for color in Table 4 or anywhere in this paper. NGC 4151 and UGC 10923 are not in the BGS or the BGS2. The NGC 4151 flux is from Edelson, Malkan, & Rieke (1987), and the UGC 10923 flux is from Mazzarella, Bothun, & Boroson (1991) in general there is excel-

### Table 3

| Asteroid        | Predicted Flux (Jy) | Counts \( \Sigma 1–10 \) | Counts \( \Sigma 1–10 \) Detector 5 | Resp.* 21–10 | Resp.* Detector 5 |
|-----------------|---------------------|--------------------------|----------------------------------|-------------|------------------|
| 01/06/1994:     |                     |                          |                                  |             |                  |
| 1 Ceres         | 145 ± 14            | 24375 ± 698              | 11088 ± 216                      | 196.3 ± 17  | 84.8 ± 6         |
| 52 Europa       | 39.4 ± 4            | 7520 ± 562               | 3319 ± 151                       |             |                  |
| 97 Klotho       | 10.5 ± 1            | 2168 ± 342               | 858 ± 91                         |             |                  |
| 08/12/94 and 08/16/94: |           |                          |                                  |             |                  |
| 2 Pallas        | 74.0 ± 7            | 8914 ± 961               | 3829 ± 231                       | 125.5 ± 18  | 53.9 ± 6         |
| 08/26/95:       |                     |                          |                                  |             |                  |
| 704 Interamnia  | 43.9 ± 4            | 7769 ± 625               | 3889 ± 250                       | 239.5 ± 24  | 113.1 ± 10       |
| 56 Melete       | 21.1 ± 2            | 5970 ± 492               | 2711 ± 190                       |             |                  |
| 08/29/1995:     |                     |                          |                                  |             |                  |
| 704 Interamnia  | 43.1 ± 4            | 1067 ± 151               | 452.7 ± 25.7*                    | 30.4 ± 3    | 13.0 ± 1         |
| 386 Siegna      | 19.5 ± 2            | 656 ± 45                 | 283.4 ± 12*                      |             |                  |

* Derived responsivity for \( \Sigma 1–10 \) detectors. Corrected for filter response of the asteroids. See §4.1 for details.

### Table 4

| Galaxy            | 100 μm Flux from Det. 5 (Jy) | 100 μm Flux from Sum (Jy) | 100 μm Flux from IRAS* (Jy) |
|-------------------|------------------------------|---------------------------|-----------------------------|
| MCG +42-04-025... | 7.4 ± 1.0                    | 8.0 ± 1.5                 | 9.6 ± 0.2                   |
| III Zw 35         | 15.0 ± 1.3                   | 13.2 ± 2.1                | 13.7 ± 0.2                  |
| UGC 02369         | 10.9 ± 1.1                   | 11.1 ± 1.6                | 11.1 ± 0.2                  |
| NGC 1275          | 6.0 ± 0.7                    | 7.5 ± 1.5                 | 6.9 ± 0.4                   |
| VII Zw 31         | 9.1 ± 1.7                    | 7.9 ± 2.9                 | 10.4 ± 0.1                  |
| UGC 05101         | 18.4 ± 2.0                   | 19.2 ± 3.4                | 21.2 ± 0.2                  |
| NGC 3110          | 15.1 ± 1.5                   | 15.8 ± 1.9                | 23.2 ± 0.1                  |
| NGC 4151          | 3.7 ± 0.9                    | 4.1 ± 1.9                 | 8.6 ± 0.4                   |
| UGC 08696         | 17.7 ± 2.1                   | 17.3 ± 2.9                | 22.4 ± 0.1                  |
| NGC 6090          | 9.3 ± 1.9                    | 8.4 ± 2.4                 | 9.3 ± 0.1                   |
| NGC 6286          | 20.7 ± 3.5                   | 21.7 ± 4.5                | 22.0 ± 0.1                  |
| IRAS 1713 + 53    | 7.5 ± 1.6                    | 6.4 ± 2.7                 | 8.4 ± 0.1                   |
| IRAS 1720–00      | 24.8 ± 3.2                   | 19.4 ± 4.0                | 37.6 ± 0.5                  |
| UGC 10923         | 8.7 ± 1.0                    | 9.2 ± 1.4                 | 10.2 ± 1.1                  |
| NGC 7469          | 42.9 ± 5.3                   | 40.5 ± 6.9                | 34.9 ± 0.6                  |
| NGC 7541          | 36.0 ± 4.5                   | 38.7 ± 6.0                | 40.6 ± 0.1                  |
| Zw 475.056        | 11.5 ± 1.4                   | 10.1 ± 2.3                | 11.6 ± 0.1                  |
| NGC 7625          | 19.5 ± 3.2                   | 19.7 ± 3.1                | 17.2 ± 0.1                  |
| NGC 7770          | 3.5 ± 1.7                    | 6.9 ± 2.0                 | ...                         |
| NGC 7771          | 34.4 ± 3.4                   | 37.6 ± 4.5                | 37.4 ± 0.9                  |
| Markarian 331     | 24.2 ± 2.2                   | 22.5 ± 2.8                | 20.9 ± 0.2                  |
| UGC 12915         | 9.7 ± 1.3                    | 11.6 ± 1.9                | 13.4 ± 0.2                  |

* IRAS fluxes are uncorrected for color from BGS, BGS2, Edelson et al. 1987 (for NGC 4151), or Mazzarella et al. 1991 (for UGC 10923).
lent agreement between our observed and the (non–color-corrected) \textit{IRAS} fluxes.

4.2. Resolution

To determine if the galaxy was resolved or not, the profile from detectors 1–10 is compared with the point-source profile (PSP). The profile of IRC +10420 was defined as the PSP on those flights on which that bright source was observed. For the 1994 January observations, the profile of the high S/N asteroid 1 Ceres was used as the PSP. While the fainter asteroids gave adequate S/N for flux calibration, IRC +10420 and Ceres profiles were most useful for generating accurate point-source profiles.

If the galaxy is strongly emitting on scales greater than 20', its profile will be noticeably more extended than the PSP. In the upper parts of Figures 2–23, the profile of each galaxy observed is compared to the PSP in two ways. One PSP is scaled and shifted so that it is normalized to the peak signal of the galaxy (dashed lines), usually in detector 5. The dotted lines are point sources with the \textit{IRAS} flux shifted to the same offset as that of the Gaussian curve fit through the five central detectors in the profile. These latter dotted lines are what a point source with the \textit{IRAS} 100 \textmu m flux would have looked like if it were centered on our array in the same way as the galaxy.

The width of the best-fit Gaussian gives the first estimate of the size of the FIR-emitting region. If it is assumed the galaxy profile is intrinsically Gaussian then deconvolution is trivial, \( \text{FWHM}^2_{\text{observed}} = \text{FWHM}^2_{\text{source}} + \text{FWHM}^2_{\text{PSP}} \) and allows determination of the Gaussian size of the source, \( D_g = \text{FWHM}_{\text{source}} \). In addition, a model of the galaxy disks was used such that \( I = I_0 \exp(-r/r_0) \) with a total flux equal to the flux found from the sum of detectors 1–10. The best fit \( r_0 \) by a two-dimensional convolution of the model with the two-dimensional PSP (with a width of \( \sim 40' \) on \( \chi \)) was then found. The exponential disk size \( D_e \) is then simply \( 2 \times r_0 \). The results of the fits to the profiles, \( D_g \) and \( D_e \), are given in Table 5.

If the profile does not show clear evidence for extended FIR emission by comparison with the shape of the PSP, then the photometry may reveal more subtle evidence for extension. The \textit{IRAS} beam is \( \sim 2' \times 4' \) at 100 \textmu m. Our “beam” for a single detector is \( \sim 36' \) \textit{IRAS} if the larger point-source spread in the direction perpendicular to the long axis of the array is considered. Our “beam” for the entire array is \( \sim 40' \times 100' \). If the detected flux is smaller than the \textit{IRAS} flux, and the source has not varied in brightness since the \textit{IRAS} observations, it can be argued that the angular distribution of the FIR is extended such that some of the flux is outside of the beam but inside the \textit{IRAS} beam.

| Galaxy          | FWHM Gaussian \( (D_g \text{ in arcsec}) \) | \( 2 \times r_0 \) from Fit \( (D_e \text{ in arcsec}) \) | \( 2 \times r_0 \) from Fluxes \( (\text{arcsec}) \) | Resolved \( \text{?}^d \) |
|-----------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|-----------------|
| MCG +02-04-025  | 19.0                                        | 11.0                                        | 12.9                                        | \( \sim Y \)    |
| III Zw 35       | 8.2                                         | <12                                         | ...                                         | N               |
| UGC 02369       | <7                                          | <12                                         | 8.4                                         | Y               |
| NGC 1275        | 30.0                                        | 17.0                                        | 10.1                                        | Y               |
| VII Zw 31       | <8                                          | <7                                          | 10.0                                        | N               |
| UGC 05101       | 20.6                                        | <12                                         | 10.2                                        | \( \sim Y \)    |
| NGC 3110        | 23.7                                        | 13.0                                        | 22.6                                        | Y               |
| NGC 4151        | 19.7                                        | <12                                         | 24.7                                        | N               |
| UGC 08690       | 3.0                                         | <12                                         | 12.3                                        | \( \sim Y \)    |
| NGC 6090        | 12.5                                        | <12                                         | 5.4                                         | N               |
| NGC 6286        | 21.3                                        | 12.0                                        | 7.9                                         | \( \sim Y \)    |
| IRAS 1713+53    | <8                                          | <12                                         | 9.5                                         | N               |
| IRAS 1720–00    | <7                                          | <12                                         | 16.0                                        | \( \sim Y \)    |
| UGC 10923       | 20.2                                        | 11.0                                        | 10.6                                        | Y               |
| NGC 7469        | 14.0                                        | 7.0                                         | ...                                         | \( \sim Y \)    |
| NGC 7541        | 23.0                                        | 12.5                                        | 9.7                                         | Y               |
| Zw 475056       | 4.5                                         | <12                                         | 5.8                                         | N               |
| NGC 7625        | 21.8                                        | 13.0                                        | ...                                         | Y               |
| NGC 7770        | ...                                         | ...                                         | ...                                         | \( \sim Y \)    |
| NGC 7771        | 16.3                                        | <12                                         | ...                                         | N               |
| Markarian 331   | 12.3                                        | <12                                         | ...                                         | N               |
| UGC 12915       | 23.4                                        | 14.0                                        | 14.0                                        | Y               |

\( ^{c} \text{FWHM of emitting region from one-dimensional fit assuming the spatial distribution of the flux is Gaussian and the convolving beam is a Gaussian of } \sigma = 15.6' \text{ (FWHM = 26').} \)

\( ^{d} \text{Scale size of the galaxy with a model where } I = I_0 e^{-r^2/\sigma^2}. \) The two-dimensional galaxy model is convolved with a two-dimensional PSF and a one-dimensional fit is made by the calculated flux in detectors 1–10 with the observed flux.

\( ^{e} \text{Scale size of the galaxy with a model where } I = I_0 e^{-r^2/\sigma^2}. \) Calculated from the detector 5 and \textit{IRAS} fluxes (Table 3) assuming a “beam” of 36' for detector 5 and 4' for the \textit{IRAS} flux.

\( ^{f} \text{Do we resolve the FIR emission from the galaxy? Y means we do, } \sim Y \text{ means we have some evidence for extension, and N means we see none. Note that objects for which the core is unresolved by comparison with the point-source profile can still show evidence for extended emission.} \)
Assuming the same exponential disk model mentioned above, we solved for $r_0$ for each galaxy using the detected flux from detector 5 and the IRAS flux. These values are also included in Table 5.

The sizes quoted in Table 5 can be considered significant only for those galaxies that show extension with respect to the point-source profiles in Figures 2–23. Most of the galaxies with $D_g < 20'$ in Table 5 are indistinguishable from point sources, and so the values given in Table 5 represent an upper limit to the size from our modeling. Those galaxies with $D_g > 20'$ in Table 5 are convincingly extended with respect to the point-source profiles, and the sizes quoted only for those galaxies that show extension with respect to the point-source profiles, and the sizes quoted represent the actual size of the galaxy at 100 $\mu$m.

The pointing errors mentioned in §§ 3 and 4.1 would tend to make the galaxy profiles larger than they actually are because while we can directly guide on the optical images of the calibrating objects and assure that the position of the array does not change relative to them, we offset-guide on most of the galaxies and thus have less assurance that the array did not shift significantly over the course of the observation. Assuming observation for half the time with the FIR core centered on detector 5 and half the time centered between detectors 4 and 5 ($\sim 7'$ away) matching the displacement of the calibrating asteroid observed at the end of the 16 August flight), the sizes we estimate in Table 5 for a galaxy with a $D_e \sim 20'$ are only 10% larger than they would be if the pointing were perfect. The sizes for the galaxies with $D_e \sim 12''$ are also only 10% too large if it is assumes that the diffraction spot moved with respect to the detector array. For galaxy FWHM values smaller than $D_e \sim 20'$ in the Gaussian model or $D_e \sim 12''$ in the exponential disk model, the uncertainties due to possible mispointing are larger, but we do not consider them resolved, in any case.

The widths of the point-source profiles obtained on different flights and different flight series are the same to within 5%. These differences are dominated by tracking errors. Assuming that the galaxy profiles have the same uncertainty in widths, standard propagation means the values with Gaussian sizes of $\sim 20'$ given in Table 5 are good to within $\sim 15\%$, not including the possible systematic uncertainty of up to 10% due to mispointing. For both the random and the possible systematic error (due to pointing problems), the uncertainty in the quoted widths decreases with greater size, so those galaxies with Gaussian sizes much greater than 20' have more accurate sizes than those for the less extended galaxies.

5. RESULTS

5.1. Derived Characteristics

5.1.1. Temperatures, Optical Depths, and Emissivity Exponents

For a single uniform slab of dust, the flux observed at a particular wavelength $\lambda$ is

$$S_\lambda = B_\lambda(T_d)Q_\lambda \Omega_\lambda,$$

(1)

where $B_\lambda(T_d)$ is the Planck function at the dust temperature $T_d$, $Q_\lambda$ is the dust emissivity at $\lambda$, and $\Omega_\lambda$ is the apparent size of the slab. Equation (1) is often used to derive a “dust temperature” from the 60 and 100 $\mu$m IRAS FIR fluxes by assuming (1) the galaxy contains only a single slab of dust with a single temperature, (2) $\tau_\lambda$ is very small at FIR wavelengths so that $Q_\lambda \propto [1 - e^{-\tau_\lambda}]$ reduces to $Q_\lambda \propto \tau_\lambda$, and (3) $\tau_\lambda \propto \lambda^{-n}$, where $n$ is the emissivity index usually given a value 1–2. Condition (1) above implies among other things that $\Omega_{60} = \Omega_{100}$ and conditions (2) and (3) give $Q_{60}/Q_{100} = (60/100)^n$ so that with $S_{60}/S_{100}$, one can solve for $T_d$.

Clearly this method has its shortcomings. Dust does not congregate in simple slabs at single temperatures, and the temperature one calculates depends on the assumed value for $n$. In addition, colder dust emitting primarily at wavelengths longer than 100 $\mu$m will not be detected. Thus the temperature given by this single-slab method cannot even be realistically classified as an average or median dust temperature but perhaps only as a representative temperature for the warm dust in the system. In addition, the far-infrared optical depths thus obtained are also likely to be biased low. This biasing has been discussed by Xu & Helou (1996).

Despite the shortcomings of the simple slab method, we use it to estimate representative dust temperature for the purposes of intercomparison, retaining assumptions (1) and (3). The typically two to three points of FIR data available for each galaxy are not enough to support models of greater complexity, such as models with several slabs at different temperatures. Infrared Space Observatory (ISO) broadband observations of NGC 6090 (Acosta-Pulido et al. 1996) show that both hotter and colder dust exists. However, the 60 and 100 $\mu$m points still accurately model the dominant 20–50 K dust feature in both Seyfert (Rodriguez Espinosa et al. 1996) and starburst galaxies.

In this analysis, the IRAS fluxes at both 60 and 100 $\mu$m are used because we did not measure at 60 $\mu$m and the large-beam IRAS fluxes are more likely to be spatially consistent with each other. As will be discussed below, occasionally our 100 $\mu$m flux is significantly different from the IRAS flux, usually because our smaller beam is pointed at only one of a cluster of galaxies which were all in the IRAS beam. In these cases our 100 $\mu$m flux was used with a 60 $\mu$m flux scaled so that our 60/100 ratio matches that of the IRAS fluxes. In this way, the $T_d$ generated is always close to the $T_d$ that the IRAS fluxes would give without any further information. It is also important to note that by using data from both our 100 $\mu$m observations and IRAS fluxes from an epoch about 10 yr earlier, we are assuming that the FIR fluxes of the galaxies observed were constant from the IRAS epoch to that of our observation.

Our high angular resolution data add the advantage of defining $\Omega_{100}$ and, by assumption (1) above, $T_d$ for the other wavelengths for which we have data. The structural information allows us to calculate $\tau_{100}$ at the same time $T_d$ is derived, but with a few notable exceptions of high optical depth, the $T_d$ as calculated by this simple model is insensitive to the dust region size.

For Table 6, we define the angular size of a dust emission region in a galaxy, $\Omega_{100}$, as the size of a circle with the diameter of the galaxy size as defined or limited by $D_e$. The scale length fitted to the profile was used instead of the scale length derived from the flux in detector 5 and the IRAS flux because it not only more accurately measures the size of the core (and only the core) but also uses the information from many detectors instead of just one. For Table 7 $D_e$ is used for those galaxies that we were able to resolve. An emissivity exponent $n = 1.5$ was used for Tables 6 and 7.

For those galaxies with measurements at longer wavelengths in the literature, the extra fluxes were used to derive $n$ along with the derived dust temperature and the optical
A value of properties can be used to estimate the visual extinction is similar to dust in the solar neighborhood, observed dust we attempt, for example, to use the sizes of $H_a$ used. This extinction may be particularly important when

Having derived the optical depth, and assuming the dust that the ratio of 60 and 100 $\alpha$ point we used our 100 $\alpha$ point and a 60 $\alpha$ point scaled so that the ratio of 60 and 100 $\alpha$ fluxes is the same as for IRAS.

Estimate the size of the central starburst. A high $A_V$ value implies that the $H_a$ size may be unreliable. The calculated values of $A_V$ we used and what they imply for each galaxy are included in § 5.2. They were taken from (in order of preference) Tables 8, 6, and 7.

It is important to understand that the single-slab method we use to determine $A_V$ is incapable of dealing with more complicated material distributions, and so it is risky to assume that our derived $A_V$ applies uniformly over the

depth at 100 $\mu$m. The results are in Table 8; the value of $n$ varies from 1.5 to greater than 2.2, but most estimates remain close to a typical galactic value of $n = 1.5$.

Having derived the optical depth, and assuming the dust is similar to dust in the solar neighborhood, observed dust properties can be used to estimate the visual extinction $A_V$. A value of $\sim 750$ for $A_V/\tau_{100}$ (Makinet al. 1985) was used. This extinction may be particularly important when we attempt, for example, to use the sizes of $H_a$ regions to estimate the size of the central starburst. A high $A_V$ value implies that the $H_a$ size may be unreliable. The calculated values of $A_V$ we used and what they imply for each galaxy are included in § 5.2. They were taken from (in order of preference) Tables 8, 6, and 7.

It is important to understand that the single-slab method we use to determine $A_V$ is incapable of dealing with more complicated material distributions, and so it is risky to assume that our derived $A_V$ applies uniformly over the

| Galaxy      | $60 \mu m^a$ (Jy) | $100 \mu m^a$ (Jy) | $D_e$ (arcsec) | $\tau_e^b$ (K) | $\tau_{100}^b$ | $A_V^c$ |
|-------------|------------------|------------------|----------------|---------------|---------------|--------|
| MCG +02-04-025 ... | 8.9              | 8.0              | 19.0           | 45            | $7.2 \times 10^{-4}$ | 0.5    |
| III Zw 35    | 11.9             | 13.8             | $< 12.0$       | $\sim 40$    | $> 4.8 \times 10^{-3}$ | >3.6   |
| UGC 02369    | 7.9              | 11.1             | $< 12.0$       | $\sim 37$    | $> 5.3 \times 10^{-3}$ | >3.9   |
| NGC 1275     | 7.4              | 6.9              | 17.0           | 44            | $8.4 \times 10^{-4}$ | 0.6    |
| VII Zw 31    | 5.9              | 10.4             | $< 7.0$        | $\sim 34$    | $> 2.0 \times 10^{-2}$ | >15.0  |
| UGC 05101    | 13.0             | 21.3             | $< 12.0$       | $\sim 35$    | $> 1.3 \times 10^{-3}$ | >9.5   |
| NGC 3110     | 8.0              | 15.8             | 13.0           | 32            | $1.1 \times 10^{-3}$ | 8.3    |
| NGC 4151     | 3.2              | 4.1              | $< 12.0$       | $\sim 38$    | $> 1.7 \times 10^{-3}$ | >1.3   |
| UGC 08696    | 22.1             | 22.4             | $< 12.0$       | $\sim 42$    | $> 6.3 \times 10^{-3}$ | >4.7   |
| NGC 6090     | 6.3              | 9.3              | $< 12.0$       | $\sim 36$    | $> 4.8 \times 10^{-3}$ | >3.6   |
| NGC 6286     | 8.4              | 21.7             | 12.0           | 30            | $2.6 \times 10^{-2}$ | 20.0   |
| IRAS 1713 +53| 6.4              | 8.4              | $< 12.0$       | $\sim 37$    | $> 3.6 \times 10^{-3}$ | >2.7   |
| IRAS 1720 -00| 17.9             | 19.4             | $< 12.0$       | $\sim 42$    | $> 6.0 \times 10^{-3}$ | >4.2   |
| UGC 10923    | 4.7              | 10.2             | 11.0           | 31            | $1.1 \times 10^{-2}$ | 8.3    |
| NGC 7469     | 27.7             | 34.9             | 7.0            | 39            | $4.0 \times 10^{-2}$ | 30.0   |
| NGC 7541     | 20.6             | 40.6             | 12.5           | 33            | $3.0 \times 10^{-2}$ | 23.0   |
| Zw 475.056   | 8.8              | 11.6             | $< 12.0$       | $\sim 37$    | $> 5.0 \times 10^{-3}$ | >3.8   |
| NGC 7625     | 8.6              | 17.2             | 13.0           | 32            | $1.2 \times 10^{-2}$ | 9.0    |
| NGC 7770     | 2.6              | 4.8              | $< 12.0$       | $\sim 33$    | ... | ... |
| NGC 7771     | 17.8             | 32.6             | $< 12.0$       | $\sim 33$    | $> 2.3 \times 10^{-2}$ | >17.0  |
| Markarian 331| 17.3             | 20.9             | $< 12.0$       | $\sim 32$    | $> 7.7 \times 10^{-3}$ | >5.8   |
| UGC 12915    | 5.4              | 11.6             | 14.0           | 31            | $7.7 \times 10^{-3}$ | 5.8    |

$^a$ Fluxes quoted are from IRAS unless the 100 $\mu$m IRAS flux is beyond our errors or a companion galaxy complicates the system. See § 5.2 to determine the source of the flux we used in any particular galaxy. Usually if we did not use the IRAS point we used our 100 $\mu$m point and a 60 $\mu$m point scaled so that the ratio of 60 and 100 $\mu$m fluxes is the same as for IRAS.

$^b$ These parameters derived from simple single slab model with an emitting region area $\pi (D_e)^2$ and $n = 1.5$ where dust emissivity, $Q \sim \lambda ^{-n}$.

$^c$ Using $A_V/\tau_{100} = 750$ (Makinet al. 1985).
| \( \lambda \) (\( \mu m \)) | Flux (Jy) | References | \( D_\tau \) (arsec) | \( T_\odot^a \) (K) | \( \tau_{100}^a \) | \( A_\nu b \) | \( n^a \) |
|-----------------|-----------|-------------|-----------------|----------------|----------------|----------------|------|
| **UGC 05101:**  |           |             |                 |                 |                |                |      |
| 60 ............ | 13.0      | 1           | <12.0           | ~35             | >1.3 \times 10^{-2} | >8.5           | ~1.50 |
| 100 ........... | 21.3      | 1           |                 |                 |                |                |      |
| 350 ........... | <2.644    | 2           |                 |                 |                |                |      |
| 450 ........... | 1.433     | 2           |                 |                 |                |                |      |
| 800 ........... | 0.143     | 2           |                 |                 |                |                |      |
| 1100 .......... | 0.068     | 2           |                 |                 |                |                |      |
| 1250 .......... | <0.036    | 3           |                 |                 |                |                |      |
| **NGC 3110:**  |           |             |                 |                 |                |                |      |
| 60 ............ | 8.0\(^c\) | 1, 4        | 13.0            | 32              | >1.1 \times 10^{-2} | 8.3            | 1.55  |
| 100 ........... | 15.8      | 4           |                 |                 |                |                |      |
| 1250 .......... | 0.033\(^c\) | 3, 4       |                 |                 |                |                |      |
| **UGC 08696:** |           |             |                 |                 |                |                |      |
| 60 ............ | 22.1      | 1           | <12.0           | ~42             | >6.4 \times 10^{-3} | >4.8           | ~1.51 |
| 100 ........... | 22.4      | 1           |                 |                 |                |                |      |
| 350 ........... | 1.004     | 2           |                 |                 |                |                |      |
| 450 ........... | 0.707     | 2           |                 |                 |                |                |      |
| 800 ........... | 0.084     | 2           |                 |                 |                |                |      |
| 1100 .......... | 0.051     | 2           |                 |                 |                |                |      |
| 1250 .......... | <0.063    | 2           |                 |                 |                |                |      |
| 1300 .......... | 0.032     | 3           |                 |                 |                |                |      |
| **UGC 6090:**  |           |             |                 |                 |                |                |      |
| 60 ............ | 6.3       | 1           | <12.0           | ~31             | >8.9 \times 10^{-3} | >6.7           | ~2.28 |
| 100 ........... | 9.3       | 1           |                 |                 |                |                |      |
| 1300 .......... | 0.003     | 6           |                 |                 |                |                |      |
| **NGC 6286:**  |           |             |                 |                 |                |                |      |
| 60 ............ | 8.4       | 7           | 12.0            | 29              | 3.2 \times 10^{-2} | 24.0           | 1.77  |
| 100 ........... | 21.7      | 4           |                 |                 |                |                |      |
| 1250 .......... | 0.040     | 3           |                 |                 |                |                |      |
| **UGC 10923:** |           |             |                 |                 |                |                |      |
| 60 ............ | 4.7       | 8           | 11.0            | ~28             | >1.9 \times 10^{-2} | >14.5          | >2.20 |
| 100 ........... | 10.2      | 8           |                 |                 |                |                |      |
| 1300 .......... | <0.006    | 6           |                 |                 |                |                |      |
| **NGC 7469:**  |           |             |                 |                 |                |                |      |
| 60 ............ | 27.7      | 1           | 7.0             | ~37             | >4.6 \times 10^{-2} | >35.0          | >1.69 |
| 100 ........... | 34.9      | 1           |                 |                 |                |                |      |
| 1250 .......... | <0.033    | 3           |                 |                 |                |                |      |
| **NGC 7541:**  |           |             |                 |                 |                |                |      |
| 60 ............ | 20.6      | 1           | 12.5            | 32              | 3.4 \times 10^{-2} | 26.0           | 1.67  |
| 100 ........... | 40.6      | 1           |                 |                 |                |                |      |
| 1250 .......... | 0.067     | 3           |                 |                 |                |                |      |
| **NGC 7771:**  |           |             |                 |                 |                |                |      |
| 60 ............ | 17.8\(^d\) | 1, 4        | <12.0           | ~33             | >2.3 \times 10^{-2} | >17.0          | ~1.49 |
| 100 ........... | 32.6\(^d\) | 1, 4        |                 |                 |                |                |      |
| 1250 .......... | 0.070     | 3           |                 |                 |                |                |      |
| **Markarian 331:** |       |             |                 |                 |                |                |      |
| 60 ............ | 17.3      | 1           | <12.0           | ~35             | >1.5 \times 10^{-2} | >8.6           | >2.01 |
| 100 ........... | 20.9      | 1           |                 |                 |                |                |      |
| 1300 .......... | <0.009    | 6           |                 |                 |                |                |      |

- These parameters are derived from a simple single slab model with an emitting region area = \( \pi (2 \times \text{FWHM})^2 \) and \( Q \propto \lambda^{-n} \).
- Using \( A_\nu /\tau_{100} = 7.50 \) (Makinen et al. 1985).
- We use our "small-beam" 100 \( \mu m \) flux for NGC 3110, so the 60 and 1250 \( \mu m \) points quoted here are scaled so that the ratio of each to the 100 \( \mu m \) flux remains the same as in was for the large-beam (IRAS) flux.
- The IRAS flux is a combination of NGC 7770 and 7771. The value we quote here is an estimate for NGC 7771 only using the BGS flux as a starting point. See § 5.2.19 for details.

**REFERENCES**:— (1) BGS; (2) Rigopoulou et al. 1996a; (3) Carico et al. 1992; (4) This paper; (5) Krügel et al. 1988; (6) Chini et al. 1992; (7) Surace et al. 1993; (8) Mazzarella et al. 1991.
central emitting region of a galaxy. It is much safer to use it to estimate roughly the amount of visual extinction from a FIR-emitting region.

5.1.2. The $q$-Value

The high-resolution observations allow us to determine more accurately how much FIR flux is coming from galaxies and galaxy systems that were unresolved by IRAS. For galaxy pairs this allows a determination of the $q$-value (the ratio of FIR to radio flux) for each galaxy in the pair instead of for the system as a whole. For isolated galaxies it may allow the determination of this $q$-value for the central regions of the galaxy, independent of its outer regions.

The $q$-value is of interest because it is very nearly constant for a wide variety of galaxies with luminosities between $10^9$ and $10^{13} L_\odot$ (Condon et al. 1991a, hereafter CHYT). This constancy is remarkable because of the completely different mechanisms by which the FIR and radio emission is produced. One way to reconcile this is through star formation where new stars heat dust to cause the FIR radiation and produce supernovae that generate the non-thermal radio emission (Condon et al. 1991a), though the timescales of the energy production is quite different in these two cases.

The $q$-value is defined (Helou, Soifer, & Rowan-Robinson 1985) by

$$ q \equiv \log \left[ \frac{\text{FIR}}{3.75 \times 10^{12} \text{ Hz}} \right]/S_{1.4 \text{ GHz}}, \quad \text{(2)} $$

where $S_{1.4 \text{ GHz}}$ is in W m$^{-2}$ Hz$^{-1}$ and

$$ \text{FIR} \equiv 1.26 \times 10^{-14}(2.58 S_{60} + S_{100}) $$

is the estimated flux from 42.5 to 122.5 $\mu$m (in W m$^{-2}$) if $S_{60}$ and $S_{100}$ are IRAS survey measurements in Jy uncorrected for color (Helou et al. 1988). These are listed in Table 2 and are discussed individually in the sections below in which the new information about the far-infrared morphology bears on it.

The better determination of $q$ for an individual galaxy in a pair could help explain the source of an anomalous $q$-value for that galaxy pair. For example, in UGC 12914/5 (see § 5.2.21) a “radio bridge” between the pair lowers the system $q$-value, but we show the $q$ for the FIR-dominant UGC 12915 is normal.

Our new calculations of the $q$-value might also help determine if the most luminous IR galaxies, and OH megamaser galaxies in particular, have an IR excess that gives a higher $q$-value (Martin et al. 1989). Four OH megamaser galaxies were observed, and, when using the IRAS fluxes, the $q$-value is too high in three of them (III Zw 35, IRAS 1720–00, and Zw 475.056). Using our fluxes, however, the $q$-value is too high in III Zw 35 and Zw 475.056 and in fact is low for UGC 08696. Of course, a sample of four does not decide the issue, but little evidence for high $q$-values in OH megamaser galaxies is seen.

5.2. Discussion of Individual Galaxies

5.2.1. MCG +02-04-025

MCG +02-04-025 = IRAS 01173 + 1405 is a spiral with an optical extension of about 18” × 30” (Mirabel & Sanders 1988). In the DSS image there is a hint of a bridge of material between the galaxy and a fainter galaxy only ~1’ to the east (Fig. 2). The interaction between the galaxies might be responsible for the log$L_{\text{H I}}/L_\odot = 11.27$. Mirabel & Sanders (1988) also note that the H I line profile is not the “horned” double peak of a normal spiral but is a single peak more common to galaxies that have suffered some interaction. They detected MCG +02-04-025 in H I in both emission and absorption. From their detection they deduce an atomic gas mass greater than $3.4 \times 10^9 M_\odot$, most of which must be concentrated near the core in order to provide a sufficient optical depth to explain the absorption. Our observations show this galaxy to be marginally re-
solved at 100 \mu m (Fig. 2), with a \( D_p = 19.5 \) and a \( D_e = 11^\prime \). The galaxy profile is slightly larger than the PSP, but better evidence comes from the photometry. The entire \textsc{iras} flux is not recovered using the sum of detectors 1–10, and the detectors 11–20 show little evidence for any emission. This leaves the other side of the detector 1–10 arm of the array (to the southeast) as the place that may have the missing \textsc{iras} flux.

Using the flux from the center detector 5, the exponential disk model fit to our data gives an \( r_0 \sim 6.5 \) when compared to the larger \textsc{iras} beam measurement. This is close to but larger than the \( r_0 \sim 5^\prime \) derived using the same exponential disk model with multibeam photometry at \( K \) (Carico et al. 1990b). Using the size of \( 2 \times r_0 = 11^\prime \), our 100 \mu m flux, and a 60 \mu m flux scaled so that the \( S_{60}/S_{100} \) ratio is the same as the Soifer et al. (1989) fluxes, we derive a \( T_q = 44.6 \) and \( \tau_{100} = 2.1 \times 10^{-3} \) from which \( A_V \sim 1.6 \). The \( A_V \) derived here from the FIR fluxes and size is low considering the large gas column density implied by Mirabel & Sanders (1988).

The possible extension at FIR wavelengths is interesting when compared to the radio morphology. The estimated size of the emission region depends on the size of the interferometric array. With a synthesized 6\arcmin beam (1.49 GHz; CHSS) find a Gaussian size 2\arcsec \times 2\arcsec. With a smaller 0\farcs25 beam (8.44 GHz; CHYT) the size is only 1\farcs2 \times 0\farcs8. Also, VLBI studies found an extremely compact core with emission on 5, 10, and 50 mas scales (Lonsdale, Smith, & Lonsdale 1993; Smith, Lonsdale, & Lonsdale 1998).

The radio studies argue quite convincingly that there is a compact radio core that might even be small enough that it becomes difficult to explain the luminosity with a starburst and its supernovae (Smith et al. 1998). However, the fact that in each case the radio emission was resolved, along with the possible extension in the FIR, argue that while a central luminous radio core may exist (weak AGN or starburst), much of the FIR flux originates on larger spatial scales. If one assumes that the FIR flux is due to dust heated by a central compact source, a simple spherically symmetric dust model (Barvainis 1987) suggests that this dust might have a size \( \sim 19^\prime \). This size assumes that the luminosity of the central source in the UV matches the FIR luminosity and the dust at \( T_q = 45 \) has a clear view of the core. For dust distributed in an optically thick disk, this is unlikely. Thus, for this object, it can be concluded that while the far-infrared emission is likely to be emitted in distributed sources, the situation in principle energetically allows those sources to be heated by a central source, whether AGN or compact starburst.

5.2.2. \textit{III Zw 35}

\textit{III Zw 35} is a close pair in visible light with components to the northeast and southwest separated by about 10\arcsec (Fig. 3). The brighter northern component contains an active core (Seyfert 2) and an OH megamaser (Diamond et al. 1999; Trotter et al. 1997) and is also the likely source for the formaldehyde (\( H_2CO \)) maser emission seen from the system (Baan, Haschick, & Ugleusch 1993).

\textit{III Zw 35} was not resolved at 100 \mu m (Fig. 3), and the observed flux is almost identical to the \textsc{iras} flux. Using the BGS fluxes and the upper limit of the diameter of the emitting region of 12\arcsec, a dust temperature of \( \sim 40 \) K and an optical depth at 100 \mu m \( \tau_{100} > 4.8 \times 10^{-3} \) are obtained. The implied \( A_V \) is greater than 3.6.

The galaxy is unresolved in CHSS with a 1.49 GHz radio flux of 41.2 mJy, but CHYT resolve the galaxy at 8.44 GHz with a size of \( 0.18 \times 0.14 \). The 1.49 GHz continuum flux with the FIR flux gives a somewhat high \( q \)-value of 2.56 which may be related to the OH megamaser (see the discussion in § 5.1.2).

5.2.3. \textit{UGC 02369}

\textit{UGC 02369} is a close pair of galaxies aligned north-south and separated by about 30\arcsec (Fig. 4). The northern component is brighter in the visible and NIR (Carico et al. 1990b), but the radio positions and the fact that we recover essentially all of the \textsc{iras} flux (within our error bars) while centered on the southern component establish that the southern galaxy produces almost all the FIR flux. Mid-infrared ISO-CAM images (Hwang et al. 1999) also show this component to be dominant at those wavelengths. While VLBI maps of the source show some evidence for small-scale structure, the emission appears to be too strong and compact to come from star-forming regions. An AGN power source for the radio emission seems likely (Smith et al. 1998). Mirabel & Sanders (1988) find H i in absorption in UGC 02369 and estimate a column density of \( 2.2 \times 10^{19} \) cm\(^{-2}\) with an assumed spin temperature of 100 K.
UGC 02369 is unresolved either directly (Fig. 4) or through our flux estimates, which are consistent with IRAS within the error bars. Hwang et al. (1999) claim that the ISO-CAM source is slightly resolved at 15 µm in 3'' pixels. They do not cite a size explicitly, but it appears to be close to that of our 100 µm size limit of 12'' using this limit and the BGS 60 and 100 µm fluxes, one obtains a dust temperature $T_d \approx 36.6$ K and a visual extinction of greater than $A_V \approx 3.9$ for the system. When combined with the CHSS 1.49 GHz radio flux of 50 mJy, the $q$-value is a normal 2.32.

5.2.4. NGC 1275

NGC 1275 is a giant elliptical galaxy (Fig. 5) associated with the radio source 3C 84 at the core of the Perseus Cluster. Not only does this galaxy have a strong AGN but it also is associated with a cooling flow and two systems of low-ionization filaments, one of which is probably the remnants of a recent merger. See the Lester et al. (1995) analysis of the 100 µm flux from NGC 1275 with the same data. The optical size from the Uppsala General Catalog of Galaxies (UGC; Nilson 1973) is 3.5' x 2.5'. The core is clearly resolved at 100 µm (Fig. 5b), and it is seen that $D_{20} = 30''$ and $D_e = 17''$. The exponential disk fit from fluxes gives a size of only $D_e \approx 13''$, but given the uncertainty of the fluxes and the effective beam size, the 17'' estimate is probably more accurate. Using the single-slab model, the 60 and 100 µm fluxes from the BGS2, and the diameter of the emitting region of 17'', one obtains a dust temperature $T_d$ of 44 K and an optical depth of $A_V \approx 0.6$. Because NGC 1275 is not a spiral and the exponential disk model may not represent the galaxy well, with the Gaussian $D_{20} = 30''$ the temperature remains nearly the same but the optical depth and corresponding visual extinction drop so that $A_V \approx 0.2$ (Table 7). In any case $A_V$ is low enough that optical images should represent the population from the galaxy fairly well.

5.2.5. VII Zw 31

This galaxy is only a fuzzy blob on the POSS (Fig. 6) with an optical extent of 10'' or less. According to optical profiles from Djorgovski, de Carvalho, & Thompson (1990) the FWHM is less than 5''. These authors also mention an object $\sim 20''$ to the northwest of the galaxy that is either a companion or the remains of a merger. The large luminosity in the FIR $L_{FIR}/L_\odot = 11.6$ of VII Zw 31 only became apparent with the advent of IRAS (Fairclough 1986), but its distance of $\sim 220$ Mpc (Sanders, Scoville, & Soifer 1991) suggests not only that its angular extent will be small but that its FIR flux will be small as well.
Sage & Solomon (1987) measured the CO emission from VII Zw 31 and discovered that the galaxy contains $5 \times 10^{10}$ $M_\odot$ of gas, which is roughly half of the dynamical mass of the galaxy. Other observations (Sanders et al. 1991; Radford, Solomon, & Downes 1991; Scoville et al. 1989) have confirmed this tremendous gas mass and show that the size of the CO-emitting region is not resolved with a beam size of 7". The surface density of the gas is therefore must be greater than 1000 $M_\odot$ pc$^{-2}$. This is ~5 times greater than the mean surface density of ~170 $M_\odot$ pc$^{-2}$ of giant molecular clouds in our Galaxy (Sage & Solomon 1987; Solomon et al. 1987). Because of the large gas mass, Sage & Solomon suggested that VII Zw 31 could be a protogalactic disk that has yet to form most of its mass into stars. However, Djorgovski et al. (1990) argue that VII Zw 31 is more likely a "merger-induced starburst" that has yet to use up most of the gas acquired in the merger. New CO interferometer observations by Downes & Solomon (1998) clearly show evidence for a rapidly rotating nuclear ring on a scale of several hundred parsecs (a few arcseconds).

VII Zw 31 was not resolved by its profile and determination of its flux only marginally suggests spatial extension (Fig. 6). All of the FIR emission is thus likely to be produced within or around the CO-emitting region. In our data of VII Zw 31 detector 1 gave an anomalous and inconsistent high flux. Because of this, the baseline was taken through detectors 2, 9, and 10, and our “sum of detectors” flux is for detectors 2–10 only. Using the maximum size of the CO-emitting region as the maximum extent of the FIR (diameter = 7"), the thermal dust model gives a dust temperature $\sim 34$ K and an optical depth of $\tau_{100} > 2.0 \times 10^{-2}$, which corresponds to a large $A_V > 15$.

5.2.6. UGC 05101

UGC 05101 is a disturbed spiral galaxy extended east-west in the optical with both a large ring (Sanders et al. 1988; Whitmore et al. 1990) and a jet (Sanders et al. 1988) or tidal tail (Majewski et al. 1993) extending at least 40" to the west. This latter feature is just visible on the DSS images (Fig. 7). There is only one core in near-infrared images (Carico et al. 1990a; Genzel et al. 1998), and several theories have been advanced to account for the morphology, the FIR luminosity of $\log(L_{\text{FIR}}/L_\odot) = 11.77$, and the presence of an active core with a LINER/Seyfert 2 emission spectrum (Majewski et al. 1993). Sanders et al. (1988) explain the ring and active core of UGC 05101 as the result of an interaction with another gas-rich spiral that they claim could have already merged to the core of UGC 05101 or is hidden behind the bright disk and jet. Majewski et al. (1993) offer a
similar picture but also argue the object 17" to the southeast is a gas-poor dwarf galaxy that may have caused the ring and AGN. In addition Majewski et al. (1993) argue that the structure of UGC 05101 could be the result of two interactions, the first causing the AGN and tidal tail and the second causing the ring. Carico et al. (1990a) suggest a companion 50" to the west but do not mention the object claimed as a galaxy by Majewski et al. (1993). Radio maps (CHSS; Condon & Broderick 1988) show a weaker component object ~45" to the northeast of the main core of UGC 05101, which has no counterpart on the DSS frame (Fig. 7) or on the deep images of Sanders et al. (1988).

To within our uncertainties the inner core of UGC 05101 (detectors 4, 5, 6) was not resolved in the FIR, consistent with the small (< 5") sizes seen in the radio (CHSS; Sopp & Alexander 1991). However, in Figure 7, an apparently significant excess of flux is seen in detector 7, on the west side of the galaxy, as well as a possible slight deficit of flux at the center compared to the IRAS flux. These detectors lay along the optical jet or tidal tail that extends to the west, and detector 7 is where that tail crosses the ring. The signal in detector 7 alone could correspond to a source with a total flux of 5.8 ± 1.3 Jy. At the distance of UGC 05101 (~160 Mpc; CHSS) this corresponds to a 100 μm luminosity (νLν) of ~10^{11} L_☉. The optical images of Sanders et al. (1988) show no optical concentration at this position. The K-band images of Genzel et al. (1998) do not include this position in their field of view.

Since UGC 05101 was not resolved the minimum size D_e < 12", the IRAS fluxes, and several FIR and submillimeter points (Rigopoulou, Lawrence, & Rowan-Robinson 1996a; Carico et al. 1992) were used to produce a T_e ~ 34.7, a τ100 > 1.3 × 10^{-2}, an A_V > 8.5, and n ~ 1.50. The galaxy q-value of 2.10 is slightly low as might be expected for a galaxy with a radio-weak AGN undergoing a large starburst. The tail seen in the optical and in the FIR does not seem to have a radio counterpart. So the evidence for an extra FIR source associated with this tail makes the low q-value for this galaxy even more difficult to explain.

5.2.7. NGC 3110

NGC 3110 is a low-inclination spiral with a companion about 2' to the southwest near the end of one of its two distinct spiral arms (Fig. 8). The system has a log (L_{100}/L_☉) = 10.96 and a rather large gas mass (as estimated from CO detection by Sanders et al. 1991) of 2 × 10^{10} M_☉. This galaxy presents a fairly unique opportunity. Since it is not too far away (65 Mpc; CHSS), it subtends a substantial angle across the sky (>60' × 30'), but it is still very luminous. It provides a good opportunity to resolve a fairly typical FIR luminous galaxy.

The core of NGC 3110 is clearly resolved (Fig. 8) and our observations indicate D_e ~ 24" and a D_e ~ 13". However, the photometry strongly suggests even further extension. The detector 5 flux (corrected for minor centering) and sum of detectors 1–10 flux both are ~33% below the IRAS flux (Table 4). This suggests that not only the core that was resolved is extended, but also that the FIR emission area is extended enough that a substantial portion of the FIR flux escaped of our detector array entirely. From the flux received in detectors 11–20 (not shown here; perhaps 5 Jy) and assuming a similar amount of FIR-emitting area is spread on the other side of the detector 1–10 arm (to the east), much of the flux discrepancy can be accounted for.

The almost exact coincidence of the IRAS source with NGC 3110 suggests that little of the IRAS flux comes from the companion to the southwest. So it can be concluded that the core of NGC 3110 is extended at least on a scale of 13", and beyond the core, the disk or arms of the galaxy contribute up to 35% of the total FIR flux.

Using the derived sizes of the core, our array-summed 100 μm flux, and a 60 μm flux scaled so that the S_{100}/S_{60} ratio remains the same as for the BGS fluxes as well as a 1.25 mm point (Carico et al. 1992) scaled similarly, one obtains a core dust temperature of 32.1 K and a rather high A_V of 8.3. The CHSS radio flux includes both the core and the disk so one only has the system q of 2.22 using BGS fluxes.

5.2.8. NGC 4151

Despite the fact that NGC 4151 has a Seyfert 1 active core, it is more representative of “normal” nearby galaxies because of its relatively low luminosity of log (L_{100}/L_☉) = 9.5 (using D = 17 Mpc; Hunt & Giovanardi 1992). The source has an optical size of about 4' × 3' on the red Palomar Sky Survey plate (Nilson 1973). An ionization cone, marked by a narrow emission line region, occupies the central 10" and is extended along an axis roughly perpen-
dicular to the stellar disk. NGC 4151 was included in the target list to confirm earlier observations of large extension on the scale of ~100° at 155 μm (Engargiola et al. 1988) and 100 μm (Gaffney et al. 1992).

Somewhat surprisingly, the extension is not obvious in the FIR profiles (Fig. 9), which offers a stark contrast against the profiles of the high-luminosity galaxies. The core is not resolved, but, even more so than for NGC 3110, the entire IRAS flux is not recovered either. This suggests that much of the flux is extended beyond the effective beam of the detectors. The 1–10 detector flux sum is ~4.1 Jy, which leaves ~4.5 Jy of the large-beam IRAS flux unaccounted for. If this flux were distributed evenly over the optical disk “ellipse” seen in Figure 9a of ~150° × 75°, our observations would be insensitive to the remaining flux because of the baseline that was removed from the profiles.

Added confidence in this picture of a compact far infrared core containing about half the total flux surrounded by a very extended envelope comes from ISOHOT observations of this object (Rodríguez Espinosa et al. 1996), which give a C100 ISOHOT flux of 5–6 Jy at 100 μm in 43° pixels, compared with the 8.6 Jy IRAS flux.

Thus the disk emission is not directly detected but is only inferred from the differences in flux. If the central point source were not present, we would not have detected the galaxy at all! Our observations are not sufficient to determine if the excess IRAS flux is from the inner 100° as suggested by the evidence for extension in the Engargiola et al. (1988) data, but they do not conflict with that suggestion.

The unresolved core flux of 4.1 Jy might be due to direct (nonthermal) emission from the AGN, but an explanation based on distributed sources from the disk with a diameter of less than 1 kpc is more likely in view of the fact that the spectral slope into the submillimeter is steeper than the $\alpha \sim 2.5$, which is considered the steepest slope possible from synchrotron–self-absorption (Engargiola et al. 1988; Edelson et al. 1988). Whatever the source of flux in the unresolved core, about half of the total luminosity of NGC 4151 originates outside of that unresolved core. Little of this extended FIR flux can be due to dust heated by the AGN.

Assuming the bolometric energy production of the galaxy is about twice that which eventually comes out in the FIR from AGN-heated dust, our model (a copy of that of Barvains 1987) suggests that dust heated by the AGN should produce emission on scales of ~28″ or greater if the dust geometry were such that there was dust at this distance with a unobscured view of the AGN in the center. Emission on this scale would have been detected if dust heating by the AGN was a significant source. ISO observations (Rodríguez Espinosa et al. 1996) appear to confirm that the FIR flux is thermal emission from dust heated by stars. The FIR data fit a blackbody of $T = 36$ K, while a warmer dust component heated by the AGN has $T = 170$ K.

It is unlikely that the AGN dominates the FIR emission either from its direct emission or from the dust that it may heat, but the AGN does make its presence clear in the radio. The comparatively strong radio flux from the AGN (Condon 1987) skews the q-value to a very low value of 1.4 when we use the IRAS fluxes.

5.2.9. UGC 08696

UGC 08696 = Markarian 273 is a well-observed galaxy with an optically conspicuous jet or tail extending to the south for at least 1′ (Fig. 10). Sanders et al. (1988) included it in their sample of ultraluminous IR galaxies because of its high FIR luminosity of $\log(L_{\text{FIR}}/L_\odot) = 11.9$. It is one of the most luminous galaxies in our sample. Veilleux et al. (1995) classify the nuclear source as a LINER from the optical emission-line ratios, but it is called a Seyfert 2 elsewhere (e.g., Khachikian & Weedman 1974).

UGC 08696 contains an OH megamaser (Schmelz, Baan, & Haschick 1987), which corresponds spatially to the main optical component and main radio component (CHSS; Sopp & Alexander 1991). There are two radio components aligned northwest-southeast and separated by ~1″ with the northwest component dominating. In the NIR however, the southeast component disappears and is replaced by a component to the southwest (Majewski et al. 1993; Zhou, Wynn-Williams, & Sanders 1993; Carico et al. 1990b). In addition, Sanders et al. (1988) mention that there is a companion galaxy 40′ to the north of the main component in the direction opposite the jet. This companion appears starlike on the DSS frame.

The core of UGC 08696 is not significantly resolved directly at 100 μm (Fig. 10), but the full IRAS flux of 22 Jy (BGS) in a point source is not recovered either. The sum of detectors 1–10 gives a flux of 17 ± 3, and the detector 5 flux is a similar 18 ± 2. The optical tail also emits in the radio
Fig. 10.—UGC 08696 as in Fig. 2

(CHSS), and so the additional far-infrared flux seen in the IRAS data may be located there. The second bank of detectors crosses nearly over the companion galaxy, but in them there is no recognizable local maximum in the far-infrared emission at that position. While the excess emission can plausibly originate in the jet, it is noteworthy that Turner, Urry, & Mushotsky (1993) show a bright serendipitous X-ray source that is approximately coincident with the starlike object at the DSS image in Figure 10. Neither of these regions are sampled in the data. On the other hand, a component of emission that is spatially offset from the main peak might be expected to displace the IRAS peak. The IRAS peak is, however, coincident with the radio source.

Using our 100 μm flux and a 60 μm flux scaled so the ratio of S(60)/S(100) is the same as in the BGS, with the CHSS 1.49 GHz radio flux, one gets a q-value of 2.16, which is comparatively low. Using the IRAS fluxes the q-value becomes 2.27, much closer to the expected 2.34 ± 0.2 (Condon et al. 1991a). In addition, using other submillimeter to millimeter fluxes (Rigopoulou et al. 1996a; Krügel et al. 1988), the best-fit single-temperature dust model gives a dust emissivity exponent $n = 1.35$ when the small-beam 100 μm flux and the scaled 60 μm point are used. Using the Soifer et al. (1989) fluxes, the exponent $n = 1.51$ is derived. In general, astronomical dust is thought to have an $n = 1–2$ (Carico et al. 1992), but for every other galaxy for which we can calculate an exponent $n$, a value near or greater than 1.5 is generally obtained (Table 8).

The low q-value and low $n$ obtained with our fluxes and sizes suggest the higher IRAS 100 μm flux is a better match to the other wide-beam (full system) measurements. Simple subtraction of the our detector 1–10 flux sum from the IRAS flux gives a possible flux for the tail of 5.1 ± 2.9, which corresponds to a luminosity ($\nu L_\nu$) of $1.2 \times 10^{11} L_\odot$.

Using the BGS fluxes and the upper limit of 12″ for the FIR diameter of the emitting region (along with the submillimeter fluxes mentioned above), we obtain a best-fit dust temperature of 42.0 K and an optical depth at 100 μm of greater than $6.4 \times 10^{-3}$, which implies an $A_V > 4.8$.

5.2.10. NGC 6090

NGC 6090 is a pair of galaxies separated by ~10″ and aligned northeast-southwest (Fig. 11a). According to Martin et al. (1991) the optical cores of the two galaxies are in contact, and the system also includes “wings” (barely visible in the DSS frame), which makes the pair reminiscent of the famous “Antennae” system. The entire system has an optical size 2.8′ × 1.5 (Nilson 1973), although our DSS

Fig. 11.—NGC 6090 as in Fig. 2
image (Fig. 11) shows that the optical cores have a combined size of $20'' \times 10''$ with a larger size around the northern dominant galaxy.

Despite the fact that our array was aligned along the northeast to southwest line between the two galaxies, NGC 6090 was not resolved (Fig. 11). Essentially the entire IRAS 100 $\mu$m flux is recovered in the small beam. The approximate point source that is observed is skewed toward detector 4 as might be expected if the southwestern source were responsible for a significant part of the emission, but owing to pointing uncertainties, this cannot be confirmed. The radio map in CHSS shows that the northeastern source is dominant in the radio. Our small size ($D_p < 12''$) is consistent with the radio size of the system given by CHSS as $5'' \times 7''.$

Hwang et al. (1999) used ISOCAM images to detect some small extension of NGC 6090 at 15 $\mu$m, but their peak-to-total flux analysis did not provide quantitative spatial information that can be compared to the data presented here. Bushouse, Telesco, & Werner (1998) found little or no evidence for extension of this source at 10 $\mu$m from ground-based data, either.

ISO photometry (Acosta-Pulido et al. 1996) has given the energy distribution of NGC 6090 from 3.6 to 200 $\mu$m and has shown that the galaxies are in fact dominated by starburst-heated dust. The authors of this work suggest without elaboration that the source is resolved with ISOPHOT in the 60 $\mu$m band, though other galaxies in the field may have contributed to this impression. Acosta-Pulido et al. (1996) also suggest a second, subsidiary dust component with $T_d = 20$ K, but they do not use the 1300 $\mu$m measurement of Chini, Krügel, & Kreyssig (1992) because of the small beam size (11'') used for this measurement compared with the ISO beam size.

Since the derived angular size is less than 12'', we feel confident in using the 1300 $\mu$m point with our data. This model (without the ISO data) then gives $T_d = 31$ K, $\tau_{100} > 8.9 \times 10^{-2}$, and $n \sim 2.3$.

5.2.11. NGC 6286

NGC 6286 is an edge-on spiral in an interacting pair with the spiral NGC 6285 $\sim 1.5$ to the northwest (Fig. 12). The optical extension of NGC 6286 is $1.3' \times 1.2'$ (Nilson 1973). Unfortunately, the long axis of our array was aligned almost perpendicular to the long axis of the galaxy, and we do not get nearly as much information about FIR emission along the disk as we might have had if the detector array was in a more favorable alignment. Filaments and plumes seen in deep CCD images as well as a faint shell-like feature extending about 0.5 to the east-southeast of NGC 6286 (barely visible in our DSS image) cause Whitmore et al. (1990) to brand NGC 6286 a possible polar ring galaxy.

Despite the poor position angle, NGC 6286 may have been resolved along the polar axis (Fig. 12). The flux in detector 3 is well above the PSP, and the IRAS flux is not recovered in a point source. The $D_p = 21''$, while the $D_a = 12''$. The sum of detector 1–10 fluxes matches the IRAS flux well. The fact that the emission is still resolved although the galaxy disk is not aligned with our array suggests that the extended FIR emission is likely to be associated with some nondisk component. In this respect, we note that detector 3, which sits on the shell-like feature to the east-southeast, is well above the point-source profile. Using the size of 12'', our flux for detectors 1–10 at 100 $\mu$m and a flux from Surace et al. (1993) for NGC 6286 that excludes the contribution from NGC 6285 at 60 $\mu$m, we get the lowest dust temperature of our sample of $T_d = 28.6$ (when we also use the 1.25 mm value from Carico et al. 1992 to get $n = 1.77$). Our optical depth measurement of $\tau_{100} = 3.2 \times 10^{-2}$ translates into an $A_V = 24$.

Aside from the large deviation from a point source in detector 3, the FIR emission can be attributed to a nuclear bulge, leaving little evidence for disk emission. Radio maps (CHSS; CHYT) show only slight emission from the disk as well.

The $q$-value for NGC 6286 is 2.01, which is slightly lower than those of most other galaxies. Our higher resolution observations confirm that NGC 6285 is not responsible for the anomaly. Lonsdale et al. (1993) classify NGC 6286 (misnamed NGC 6285 in their paper) as H II spectral type, but Veilleux et al. (1995) classify it as having a LINER spectrum, so it is possible that NGC 6286 contains a weak AGN core, which adds extra radio flux and lowers the $q$-value from the strong starburst.

5.2.12. IRAS 17132+5313

IRAS 17132+5313 is a double galaxy aligned east-west with the eastern component brighter in the visible and radio (Fig. 13). The two components are separated by about 10''.

![Figure 12. NGC 6286 as in Fig. 2](image-url)
Interestingly, most studies of the system in the radio have concentrated on the weaker western component because it is very compact. The eastern component was resolved by CHSS with a size of and it has an H II-like spectrum (Veilleux et al. 1995). The western component is resolved by both CHYT and by Lonsdale et al. (1993), who classify the western source as an AGN.

The galaxy was not resolved at 100 \( \mu \text{m} \) (Fig. 13). The IRAS flux is slightly higher than the observed value but is within the uncertainties. The companion galaxy about 1\( \text{'} \) to the southeast of the dominant pair may contribute some significant flux to the IRAS value since it emits \( \sim 13\% \) of the total radio flux.

IRAS 17132+5313 was modeled with the full IRAS fluxes from the BGS and uses the unresolved upper limit of 12\( \text{'} \). The model provides a dust temperature of 37 K and an optical depth at 100 \( \mu \text{m} \) of greater than \( 3.6 \times 10^{-3} \), which corresponds to a \( A_V \) of greater than 2.7. The FIR flux along with the total CHSS 1.49 GHz radio flux of 25.8 mJy give a \( q \)-value of 2.51.

5.2.13. IRAS 17208—0014

IRAS 17208—0014 is an extremely luminous and distant system, which like VII Zw 31 seems to have a large amount of gas concentrated in a very small volume. It is formally the most luminous source in our sample and provides one of our more surprising results. From single-dish observations of the CO, Mirabel et al. (1990) obtain a molecular gas mass of \( 5.5 \times 10^{10} \, M_\odot \). Observations with the Owens Valley interferometer array get a similar amount. The CO emission is spatially unresolved and so has a scale size of less than 3\( \text{'} \). Observations in the CO \( J(2-1) \) line (Rigopoulou et al. 1996b) provide a smaller estimate for the gas mass of only \( 3.8 \times 10^9 \, M_\odot \).

IRAS 17208—0014 also contains an OH megamaser (Martin et al. 1989), suggesting a cloud in front of a continuum source, and so it is not surprising that H I is strong in absorption. The H I column density is \( 1.7 \times 10^{22} \, \text{cm}^{-2} \) if a spin temperature of 100 K is assumed.

Our 100 \( \mu \text{m} \) fluxes for IRAS 17208—0014 are \( 19.4 \pm 4 \, \text{Jy} \) (sum of detectors 1–10) and \( 24.8 \pm 3 \, \text{Jy} \) (detector 5). These are both far below the BGS2 flux of 38 Jy. The spatial distribution shows no particularly great deviation from a point source at 100 \( \mu \text{m} \) (Fig. 14). The DSS image shows a fairly crowded field, but no extended companions that could be responsible for the extra flux are apparent (Fig. 14). There are no apparent companions in the \( K \)-band either (Zenner & Lenzen 1993). Murphy et al. (1996) find no

![Figure 13](image3.png)

**Fig. 13.** IRAS 1713+53 as in Fig. 2

![Figure 14](image4.png)

**Fig. 14.** IRAS 1720—00 as in Fig. 2
indication of companions from radio maps. In the deep red band image of Murphy et al. (1996), however, an arm extends to the east about 30° from the core; it may be that IRAS detected FIR flux from this arm and the smaller beam did not. This image also shows what appears to be a bridge of emission connecting the galaxy with the starlike object 0.5 to the north, and it is possible that this bridge and separate source, which are not well sampled by the data presented here, accounts for some of the missing energy.

But these explanations are complicated by the fact that the IRAS centroid is identical to ours, suggesting that any missing flux should be symmetrically distributed around the center. Another possibility is that the FIR flux of this source is variable but radio observations at 4.85 GHz show no significant variation from 1987 to 1992 (Becker, White, & Edwards 1991; Griffith et al. 1995; Condon, Anderson, & Broderick 1995), and the source spectrum is clearly thermal throughout the infrared.

With the 1.425 GHz radio flux of 102 mJy from Condon et al. (1995) and the 4.86 GHz flux of 61 mJy from Condon et al. (1996), a power-law slope of \( \alpha = -0.42 \) (\( S_\nu \propto \nu^\alpha \)) is obtained and a 1.49 GHz value of 100 mJy from which we obtain a \( q \)-value of 2.62 when using the BGS2 FIR fluxes. The \( q \)-value with the BGS2 FIR fluxes and the 4.86 GHz value is 2.85. Both of these \( q \)-values are somewhat high. Summing the flux across our array, and using a 60 \( \mu \)m value such that the ratio between the 60 and 100 \( \mu \)m points matched the ratio of the BGS2 values, much more normal \( q \)-values of 2.33 and 2.56 are obtained for 1.49 GHz and 4.85 GHz, respectively. See § 5.1.2 for a brief discussion on the possibility that OH megamaser galaxies have high \( q \)-values.

With its very compact size (unresolved with 3° beam in CO), the simple modeling of IRAS 17208−0014 (with our 100 \( \mu \)m flux, and the IRAS 60 \( \mu \)m flux scaled so as to match the Sanders et al. 1995 flux ratio) gives a very high optical depth of \( \tau_{100} > 9.3 \times 10^{-2} \), which corresponds to an \( A_V > 70 \). This is by far the highest optical depth calculated for our sample.

### 5.2.14. UGC 10923

UGC 10923=Mrk 1116 is a multiple system with an interacting companion only 15° to the northeast of the main component. The DSS frame shows an apparent bridge connecting these components to a compact object 20° to the northwest. Another galaxy lies 50° to the southeast. Our data show conclusively that most of the FIR flux comes from the cluster galaxies on the west side (Fig. 15a). Because of its low 60 \( \mu \)m flux, UGC 10923 is not in the BGS and so is less often observed than other FIR-luminous galaxies. The object is poorly documented in the literature. Bushouse (1987) observed UGC 10923 at the 21 cm line in H I and estimates a atomic gas mass of \( 7 \times 10^9 \, M_\odot \). In addition, Bushouse provides an H\alpha image that shows a size of \( \sim 20' \) in the western group.

From the comparison to the point-source function (Fig. 15), it is clear that UGC 10923 is resolved at 100 \( \mu \)m. The H\alpha size is well matched by the 20° size of our resolved Gaussian model (\( D_e \)). Summing over all our detectors, we recover the IRAS flux (Mazzarella et al. 1991) to within our observational uncertainties.

Away from the central source, the emission appears to be distributed mostly eastward of the more distant component. That component itself does not appear to be a significant contributor to the 100 \( \mu \)m flux. The IRAS centroid is offset from the main component slightly toward the east, which is consistent with our findings.

Using the IRAS fluxes, an additional upper limit of 5.7 mJy at 1300 \( \mu \)m from Chini et al. (1992), and the \( D_e = 11' \) size of the region, a dust temperature less than 28 K, an optical depth at 100 \( \mu \)m greater than \( 2.1 \times 10^{-2} \), and a dust emissivity exponent \( n > 2.2 \) are calculated. This value for \( n \) is nearly as high as any other emissivity exponent for dust we calculate, and it is higher than the normally accepted estimates of \( n = 1-2 \) for dust (Carico et al. 1992), but its low value depends entirely on the low upper limit given by Chini et al. (1992). The \( r_{100} \) corresponds to an \( A_V > 16 \), so the H\alpha is probably leaking out of the starburst region.

No published radio fluxes were found at or near 1.49 GHz for UGC 10923, but Marx et al. (1994) give fluxes at 4.76 GHz and 10.7 GHz from which a flux at 4.85 GHz was derived. When combined with the IRAS fluxes the derived radio flux provides a normal \( q \)-value (for 4.85 GHz) of 2.68.

### 5.2.15. NGC 7469

NGC 7469 is a bright, luminous, and well-observed SBa galaxy with a Seyfert 1 core (Genzel et al. 1995; Cutri et al. 1984). The companion IC 5283 is about \( \sim 80° \) to the north.
NGC 7469 has an optical size of 100'' × 60'' (Nilson 1973), but our DSS frame shows only the core with a size of ~40'' × 20'' (Fig. 16). Near-IR profiles show a sharply peaked distribution with scale size of ~2'' (Zener & Lenzen 1993) or less (Ternrup et al. 1994; Mazzarella et al. 1994; Genzel et al. 1995). There is $1.5 \times 10^{10} M_\odot$ of H$_2$ concentrated in the central 2'' of NGC 7469 as determined by studies of CO emission (Meixner et al. 1990) and somewhat less of H I (Mirabel & Sanders 1988). Some of this gas is concentrated in a clumpy nuclear ring of radius ~1.5'' seen in radio (Wilson et al. 1991; CHYT), visible light (Mauder et al. 1994), and even at 11.7 μm (Miles, Houck, & Hayward 1994). In addition, NGC 7469 shows emission lines from polycyclic aromatic hydrocarbons (PAHs) from the extranuclear region (Miles et al. 1994; Mazzarella et al. 1994; Cutri et al. 1984). Miles et al. (1994) point out that these molecules would be destroyed by the X-ray flux from the active core of NGC 7469 and note that shielding by clumps of gas with $N_H > 10^{23}$ atoms cm$^{-2}$ could protect them.

Despite the assertion that the majority of the log$(L_{\text{FIR}}/L_\odot) = 11.2$ is concentrated within the circumnuclear ring with a ~2'' diameter (Genzel et al. 1995), a very small fraction of 100 μm flux may be seen on a considerably larger scale (Fig. 16). Our fitting and deconvolution on this high S/N object allows some superresolution and gives $D_s = 14''$ and $D_e = 7''$. While the majority of the FIR flux lies on scales well below our resolution, there may be some flux extended beyond the circumnuclear ring. Photometrically, the IRAS flux is recovered exactly, within our uncertainties, so it is not possible to use the flux deficit to estimate the size.

With our estimate of $D_e = 7''$, the single-slab model for the dust gives $\tau_{100} > 5 \times 10^{-2}$, which converts to an $A_V > 35$. This extinction cannot surround the AGN since it is easily visible in the optical. Using $N_H/A_V = 1.9 \times 10^{25}$ (Bohlin, Savage, & Drake 1978), the column density is $N_H > 6.7 \times 10^{22}$, which is high enough to adequately shield the PAHs (Miles et al. 1994).

The flux obtained for NGC 7469 used only detectors 1–9 for both the baseline and the flux by summation of detectors. This was done because of the excess flux seen by detector 10, which is close to IC 5283. While the IRAS position does not appear to be biased by this companion and the IRAS flux was recovered in detectors that excluded it, the data are suggestive that IC 5283 contributes modestly to the luminosity of the system. These two galaxies were resolved separately at 12 and 25 μm with HIRES studies on the IRAS database (Surace et al. 1993). In this study, IC 5283 was found to be less than 5% of NGC 7469 at 25 μm—a ratio that is surprisingly small given the conspicuousness of the former in our data set, in which it is probably only partly sampled. It would appear that IC 5283 has a cooler spectrum than NGC 7469.

Optical studies of this pair (Marquez & Moles 1994) show that IC 5283 is, in itself, a strongly disturbed system. There appears to be little evidence for a substantial stellar or gaseous component bridging the systems, and the lack of 100 μm emission between them (in our detectors 7–9) is therefore not surprising.

5.2.16. NGC 7541

NGC 7541 (Fig. 17) is a relatively nearby (36 Mpc; CHSS) disturbed starburst spiral with an optical size of 3.4' × 1.1' (Nilson 1973). Radio maps by CHSS and Colbert et al. (1996) also give a rather extended size of 60'' × 24'', with little central concentration. At 10 μm the small aperture (5'') to large aperture (100'') compactness ratio is $C = 0.07$ (Giuricin et al. 1994). The nonpointlike flux distributions at radio and 10 μm wavelengths suggest that the FIR flux of NGC 7541 will also be extended.

NGC 7541 has been observed often in H I (Lu et al. 1993; Oosterloo & Shostak 1993). A value of 47 mJy was used, which implies an atomic gas mass of $9 \times 10^9 M_\odot$ (Mirabel & Sanders 1988). This is approximately twice the molecular gas mass of $4.5 \times 10^9 M_\odot$ (Sanders et al. 1986). The usual ratio of molecular to atomic gas masses in FIR luminous galaxies is ~2–5 (Mirabel & Sanders 1988), and so in this respect, the ratio of ~1:2 makes NGC 7541 look more like a quiescent galaxy.

NGC 7541 was easily resolved at 100 μm along the minor axis of the galaxy (Fig. 17). The fitted Gaussian gives $D_s = 23'$, while the fitted disk model gives a $D_e = 12.5'$. A note in CHSS says the companion NGC 7537, which lies several arcminutes to the southwest, may contribute to the IRAS flux. The summed flux (38.7 ± 6.0 Jy) is consistent with the IRAS flux of 40.6 Jy, so the entire IRAS flux has been recovered despite the alignment of our array along the
minor axis of NGC 7541. These facts taken together would argue that the morphology of the 100 \( \mu \)m emission is more circular than the very elongated optical contours. If distributed like the optical emission, it would have missed most of the flux in our array.

We note parenthetically that our array position did not cover the site of the recent supernova SN 1998d, a SN Ia that was discovered 50° west and 10° north of the center.

Using the single-slab model, \textit{IRAS} fluxes, and the 1.25 mm flux from Carico et al. (1992), one gets \( \tau_{100} = 3.4 \times 10^{-2} \). This gives \( A_V = 26 \), which is not unreasonable for an edge-on spiral.

5.2.17. Zw 475.056

Zw 475.056=1C 5298 (Fig. 18) is a Seyfert 2 galaxy (Veilleux et al. 1995) that has an associated OH maser (Mirabel & Sanders 1987). The molecular gas shows a double-peaked line with a strength that corresponds to a mass of \( 9.4 \times 10^9 M_\odot \) (Mirabel & Sanders 1987). The double-peaked line is also apparent in the \textsc{hi} observations and is typical of galaxies that have not undergone interactions. The \textsc{hi} line strength suggests an atomic gas mass of \( 5.5 \times 10^9 M_\odot \) (Mirabel & Sanders 1987). Considering the fact that all the other OH megamaser sources in the sample show at least some \textsc{hi} absorption, the double-peak structure of the gas lines here may be due to foreground absorption of the galaxy (Mirabel & Sanders 1987). If it is an absorption feature, the gas masses quoted above are only lower limits.

Our profile of Zw 475.056 (Fig. 18) does not show significant evidence for extension, and our 100 \( \mu \)m point-source fluxes matches the \textit{IRAS} BGS flux well. Using \( D_e < 12'' \), a dust temperature of 38 K and an optical depth at 100 \( \mu \)m greater than \( 5.0 \times 10^{-3} \) is derived, which corresponds to an \( A_V > 3.8 \). That the \textit{IRAS} position is significantly displaced \( \mathcal{A} \) from the place where we see all the flux, and no companions that might confuse the centroiding are evident, has no obvious explanation.

VLBI observations of Zw 475.056 (Lonsdale et al. 1993) resolve the core as do the VLA observations in CHYT. These latter data show that the core of the galaxy, on scales less than an arcsecond, is oriented north-northwest–south-southeast as in the larger scale optical (Fig. 18) and \textit{i}-band (Zenner & Lenzen 1993) contours. The faint halo with \( \sim 20'' \) extent visible in the optical (see the DSS image, Fig. 18) is not visible in the \( i, H, \) and \( K \) bands. These images show only a core less than 10'' in diameter (Zenner & Lenzen 1993). This halo evidently does not contribute much of the
100 $\mu$m emission. The radio flux for Zw 475.056 at 1.49 GHz (CHSS) provides a $q$-value of 2.53, which is somewhat above the average value of 2.34. A flux at 4.85 GHz (Sopp & Alexander 1992) gives a $q$-value of 2.97, which is also higher than normal. See the discussion on OH megamasers having high $q$-values in § 5.1.2.

5.2.18. NGC 7625

NGC 7625 is a type Sa/S pec galaxy with a comparatively modest luminosity. Unlike most early-type galaxies, it happens to have a great deal of gas and dust associated with it and a large star formation rate (Li et al. 1993). A dust lane is conspicuous in the DSS image (Fig. 19). The optical size of the galaxy extends to 1.5 $\times$ 1.5 (Nilson 1973), but comparisons of the sizes of the blue light, the CO, the Hα, and the 20 cm-emitting regions along the major axis of rotation (P.A. $\sim$ 28°) show that each of these tracers give a FWHM of $\sim$10″ (Li et al. 1993). NGC 7625 has a molecular gas mass of $\sim$2.4 $\times$ 10$^9$ $M_\odot$ and an atomic mass of about the same amount (Li et al. 1993).

Our 100 $\mu$m profile (Fig. 19) is peaked between detectors 4 and 5, while the optical peak should have been between detectors 5 and 6. This suggests that the FIR is skewed slightly to the south away from the optical (Li et al. 1993) and large-beam 1.49 GHz radio (CHSS) position, which was our target. That pointing position also corresponds well to the Hα and H I center, while the CO and small-beam radio centers appear to be several arcseconds to the northwest. Significantly, the FIR peak corresponds spatially better with the prominent dust lane and the centroid of the outer optical contours.

Though our point-source flux is consistent with that of IRAS, there is some slight evidence for extension of NGC 7625 in the profile (Fig. 19), and $D_e = 21.8$ and $D_e = 13''$ is obtained, which matches the sizes of the other tracers of the starburst activity. Using the derived disk size of 13″ in the single-slab model, $T_d = 32$ K and $a_{100} = 1.2 \times 10^{-2}$ are derived, which translates into an $A_V = 9$.

5.2.19. NGC 7770/7771

NGC 7770/7771 is an interacting system with the larger spiral galaxy NGC 7771 separated from its companion to the southwest by about 80″ (Figs. 20 and 21). NGC 7771 is a luminous system that contains a well-defined starburst ring (Smith et al. 1999) with a major axis of 6". The optical morphology is strongly affected by extinction. It is found that both galaxies are emitting in the FIR, although the system is dominated by NGC 7771. Both galaxies also have optical spectra classified as H II emission–dominant (Kim et al. 1995; Veilleux et al. 1995).
The core of NGC 7771 (Fig. 21) was not spatially resolved, which argues that essentially all of the far-infrared emission comes from within the starburst ring, the diameter of which is just below our detection limit for spatial extension. The observations of NGC 7770 are too noisy to determine a size (Fig. 20), so a model to determine its optical depth was not produced. Observations of NGC 7770 do suggest that it may not be a point source, however, and the $I$-band image shown in Smith et al. (1999) shows a 20$''$ extent that has little central condensation.

Using BGS fluxes (with both the 100 and 60 $\mu$m fluxes scaled by the radio ratio) for NGC 7771 as well as the 1.25 mm point from Carico et al. (1992), a dust temperature of 33 K is obtained. The model also gives an optical depth at 100 $\mu$m $\tau_{100} > 2.3 \times 10^{-2}$ and a dust emissivity exponent $n \sim 1.49$. The $\tau_{100}$ corresponds to an $A_V > 17$.

Using the radio fluxes from CHSS and BGS fluxes give a normal $q$-value of 2.39 for the system. Despite its small flux compared to its companion, NGC 7770 is fairly luminous by itself with $\log(L_{\nu}/L_\odot) = 10.20$. This is enough to classify it as a FIR-luminous galaxy and help to confirm the suggestion that in interacting galaxies, both partners are often FIR enhanced (Surace et al. 1993; Bernlöhr 1993).

Markarian 331 (Fig. 22) is a FIR-luminous galaxy with an H II–like optical spectrum (Veilleux et al. 1995). The galaxy shows both emission and absorption in H I with an atomic gas mass greater than $9.55 \times 10^9 M_\odot$ and column density of $7 \times 10^{20}$ cm$^{-2}$ if a spin temperature of 100 K is assumed (Mirabel & Sanders 1988). The estimated molecular gas mass is $1.29 \times 10^{10} M_\odot$ (Sanders et al. 1991).

Mrk 331 (Fig. 22) is not resolved with these observations, and the flux matches the IRAS BGS flux to within our error bars. The IRAS position is offset from the radio position (CHSS) in the direction of two faint galaxies $\sim 1.5$ to the southwest. While this offset might suggest that one of the nearby companions is responsible for some of the FIR flux assigned to this object and is introducing a bias into the large-beam position centroid, our photometry does not support this explanation, and we note also that the IRAS error ellipse is fairly large.

Using the Soifer et al. (1989) FIR fluxes and an upper limit of 8.7 mJy from Chini et al. (1992), a dust temperature near 35 K is estimated, an optical depth $\tau_{100} > 1.5 \times 10^{-2}$, and a dust emissivity exponent $n > 2.01$. The corresponding $A_V > 8.6$. The $q$-value with the radio value from CHSS is a moderately high 2.51.
5.2.21. **UGC 12915**

UGC 12915 is the smaller of a closely interacting pair of galaxies (Fig. 23). UGC 12914 is only 1.5 to the southwest. Both galaxies are obviously disturbed spirals with prominent tidal tails and even a ring around UGC 12914. Radio maps (Condon et al. 1993; CHSS; Condon, Frayer, & Broderick 1991c) show not only that the galaxies are radio sources but also that the space between them is a radio source as well, such that only ~58% of the radio flux is localized around the individual galaxies. Because it is stronger in the radio and perhaps at 60 μm as well, the array was centered on UGC 12915. The second arm of the array fell between the two galaxies, allowing us to see if any of the FIR flux was coming from the radio bridge.

UGC 12915 was resolved in our first set of observations in 1994 August and found a D_q = 24″ or a D_e = 12″. Our measured 100 μm flux in detectors 1–10 was 9.9 Jy, compared to 13.4 Jy from IRAS, suggesting that about one-quarter of the emission originates elsewhere. The second arm of the array seemed to show evidence for substantial FIR emission from the radio bridge, but the uncertainty was high.

In order to confirm the photometry, the observation of UGC 12915 was duplicated in the 1995 August flight series.

The new observations (Fig. 23, Table 4) confirm the size very well; they give D_q = 24″ and D_e = 14″. The 1995 observations also match the 1994 flux estimate with a 100 μm flux of 11.6 Jy. The new observations allow for only slight FIR from the radio bridge. Condon et al. (1993) claim that about 25% of the 60 μm flux is from UGC 12914. Assuming similar colors, the difference between our 100 μm flux and the large-beam IRAS flux from BGS (13.4 Jy) is easily explained by flux from UGC 12914.

Using the disk size of 14″, our detector 1–10 summed 100 μm flux, and a 60 μm flux scaled so that the S_{60}/S_{100} ratio is the same as in the BGS, a T_g = 31 K and a τ_{100} = 7.7 × 10^{-3} are obtained for UGC 12915.

Condon et al. (1993) had assumed that the low 1.49 GHz q-value for the UGC 12914/5 system of 1.94 occurred because the radio bridge was emitting radio synchrotron but not FIR. Our observations have confirmed that there is little if any FIR from the area between the galaxies. With the 100 μm flux for UGC 12915 one can calculate its q-value independently. The 1995 August 100 μm flux in detectors 1–10 and a flux for 60 μm were used, scaled so that the S_{60}/S_{100} ratio matches the Soifer et al. (1989) flux ratio. With the Condon et al. (1993) 1.49 GHz flux for UGC 12915 of 47 mJy, q = 2.26 is calculated. This normal q-value also confirms that the abnormally low system q-value is caused by the extra radio emission from the bridge and not from the disk of UGC 12915.

6. DISCUSSION

Our observational techniques have been effective in probing the structure of far-infrared emission in galaxies on very small scales. Of the 22 galaxies, we see at least some evidence for extension of the 100 μm emission, either by comparison with point-source profiles, or by missing peak flux, in 12 (MCG +02-04-25, NGC 1275, UGC 05101, NGC 3110, UGC 08696, NGC 6286, IRAS 17208—0014, UGC 10923, NGC 7541, NGC 7625, NGC 7770, and UGC 12915). The emission from NGC 4151 appears to be very large and is mostly outside our sampling area.

There are several possible explanations for the strong FIR emission from the sample galaxies. These include (1) emission from an active galactic nucleus (AGN), (2) emission from dust heated by an AGN, (3) emission from dust heated by a massive burst of star formation, (4) emission by dust heated by a stellar population, (5) emission by dust heated by the UV photons produced by shocks in galaxy collisions, and (6) emission by dust heated by extremely hot gas from a galaxy cluster cooling flow. Clearly, not all of these mechanisms are possible in all of the galaxies in our sample. Mechanisms (1) and (2) are possible only for those galaxies with an AGN, mechanism (5) is possible only for those systems with multiple galaxies or galaxy cores, and mechanism (6) applies only to NGC 1275 because it is the lone galaxy in our sample with a cooling flow. The expected sizes of FIR-emitting regions for these mechanisms are described below and then compared to the observed sizes at 100 μm.

6.1. **Emission from AGNs and Emission from Dust Heated by AGNs**

If the core is resolved, little of the FIR emission can come directly from the pointlike AGN. For galaxies with a FIR D_q > 20″ (barely resolved), we find that 50% of the flux could come directly from a point source only if the remain-
ing emission from the galaxy disk had $D_g > 40''$. Radio maps of the galaxy disks in those galaxies that were resolved (CHSS; Condon et al. 1996) do not show substantial emission at such scales. To first order, radio distributions appear to be larger than the FIR for galaxy disks (Bicay & Helou 1990; Marsh & Helou 1995; Lu et al. 1996). So a pointlike AGN would provide less than 25% of the FIR flux to a marginally resolved source and even less to the flux of a source that is more clearly resolved.

Dust heating by the AGN is another process that might produce some of the extended emission. A model that assumes the dust is optically thin in the IR and is distributed spherically around the AGN (Barvainis 1987) suggests that in order to match both the observed FIR luminosity and ~40 K dust temperatures with a central AGN heating source, the dust must have a direct line of sight to that source (for instance, if the dust was in a warped disk—see Sanders et al. 1989) and also must be several kiloparsecs (typically > 30'') away from the AGN. Any substantial amount of dust closer to the AGN would have a higher temperature and so would move the peak emission to shorter wavelengths. In addition, the model AGN luminosity cannot be lowered to allow ~40 K dust at smaller radii or else the FIR luminosity will drop below the observed levels. Only for MCG +02-04-025 do the sizes estimated for the FIR flux from AGN-heated dust and the observed sizes match ($D_g \sim 19''$ for both), but it has an H II–like optical spectrum. Galaxies with high FIR emission tend to be complicated systems, often undergoing or having already undergone interactions. AGN activity is at least as likely to be the result of the interaction as it is likely to be a determining factor in the far-infrared energetics of the system.

6.2. Emission from Dust Heated by Starbursts

Massive star formation is a more likely source for the energy that heats the dust in FIRLGs. Most of the galaxies in the sample show clear evidence for widespread and intense star formation, usually a central region with an emission spectrum that resembles an H II region (see Table 2). The FIR-emitting region would then be expected to be similar in size to the starbursting region because the large amount of dust in typical star-forming regions causes the mean free path of the UV photons to be very small. The expected sizes of the FIR-emitting regions in this case would be variable from galaxy to galaxy but would correspond to the extent of photoionized gas, as traced by the emission lines. Most of our target galaxies show far-infrared distributions that are consistent with the spatial tracers of massive star formation.

Starburst region sizes can be assumed to be the same as that of the H z regions in galaxy images if the extinction is small or sufficiently patchy. A quick search of the literature for H z region sizes for galaxies we clearly resolved provides three galaxies, each with an H z region with FWHM ~ 20' (NGC 7625, Li et al. 1993; and UGC 10923 and UGC 12915, Bushouse 1987). These widths are a good match to the observed FIR sizes ($D_g$) listed in Table 5. So the Hz sizes support the starburst theory of FIR emission for these resolved galaxies.

6.3. Emission from Dust Heated by Older Stars

It is also possible that older stellar populations provide some of the energy to heat the dust in luminous IR galaxies (cf. Helou 1986), but unless this population is hugely in excess of that indicated by the optical and near-infrared tracers of the red stellar population, it is unlikely that they could dominate the energetics in the luminous systems. In particular, the NIR and FIR fluxes are not correlated in the most luminous FIR-luminous galaxies (Harwit et al. 1987), and the colors imply insignificant extinction toward that older population (Harwit et al. 1987; Houck et al. 1985). For the lowest luminosity galaxies in our sample, the NIR luminosities are close enough to the FIR luminosities that dust heated by red giants might contribute to the FIR. However, even these low-luminosity galaxies mostly show H II emission-line spectra and large Hz luminosities suggestive of dominance by a younger starburst. NGC 4151 is a noteworthy case, in that a large part of the far-infrared emission from that galaxy is clearly extended on a scale that is similar to the near-infrared light and over a region that has little or no ionized gas.

6.4. Emission from Other Mechanisms

Other mechanisms of heating the dust such as collisions of galaxies (Harwit et al. 1987) and the interaction of the dust with a cluster cooling flow (Lester et al. 1995) may affect certain galaxies in our sample. It is of interest, in this context, that the far-infrared emission in these systems is concentrated in one or both of the interacting components. In the interacting systems that are easily resolved by our measurements, we see no evidence for large amounts of far-infrared emission from intranuclear parts. While a large fraction of our sample seems to have undergone collisions, only a few seem to still be so close that their molecular disks could be currently colliding. The fact that these galaxies continue to produce copious FIR emission long after their collisions (e.g., $2 \times 10^7$ yr after the collision for UGC 12915; Condon et al. 1993) argues against the collision heating mechanism for most, since the gas cooling time is ~1000 times less than the collision time (Harwit et al. 1987). NGC 1275 and its associated cooling flow may be special in this regard (Lester 1995).

7. CONCLUSION

We have observed the distribution of 100 $\mu$m continuum emission in 22 galaxies, most of which have $L_{FIR} > 10^{11} L_\odot$. The structure is clearly resolved ($D_g > 20''$, $D_g > 12''$) in six of them. There is some evidence for extension in seven others. In these galaxies, extended emission appears to constitute a significant percentage of the far-infrared continuum emission on scales of 5–10 kpc. This is a substantially larger region than the kiloparsec-scale nuclear starbursts that have been seen in nearby galaxies and may be best understood on the basis of close mergers that are optically shrouded by extinction.

For every resolved and possibly resolved source in our sample except for MCG +02-04-025, NGC 4151, and NGC 1275, we are able to eliminate all possible methods for FIR production except for starburst-heated dust. Of the galaxies we could not resolve, most show correspondingly small starburst regions, and our size limits are consistent with those regions dominating the energetics.

In a few cases, most notably NGC 3110, the disk of the galaxy makes a substantial contribution to the FIR flux. The contribution of the disk of NGC 3110 and the extended emission outside the bright cores in MCG +02-04-025 and NGC 6286 suggest that it is imprudent to assume all of the
FIR flux in more distant FIR-luminous galaxies (that we do not resolve) is concentrated in the core. A better universal model for the FIR flux distribution for these galaxies would be a strong central core on top of an extended “plateau” of emission from the disk.

For the systems we resolved, we used the core sizes in a simple, single-slab emission model to estimate not only the dust temperature $T_d$ but also the optical depth at 100 $\mu$m $\tau_{100}$, assuming a dust emissivity exponent of $n = 1.5$ (emissivity $Q \propto \lambda^{-n}$). In addition, when they were available, we used fluxes at longer wavelengths that we assumed were still associated with the thermal dust emission. The additional flux measurements when combined with the measurements at 60 and 100 $\mu$m allow us to solve for the emissivity exponent, $n$, as well. These measured values of $n$ are all equal to or greater than 1.5, and two far exceeded the expected range of 1–2 (e.g., Carico et al. 1992; see Table 8).

With the values of $\tau_{100}$, we calculated an estimate for the visual extinction (via $A_V/\tau_{100} \sim 750$ for our galaxy; Makinen et al. 1985). Assuming that the stars are well mixed with the dust, we can tell how much the visible light from the galaxy (and in particular the FIR flux-producing region) is extinguished. The single-slab model is incapable of dealing with geometrical situations that almost surely exist in all of these galaxies such as a central condensation of material. Therefore the $A_V$ estimates are only a rough indicator of the true extinction of the galaxy. The $A_V$ estimates vary from an insignificant value of $\sim 0.2$ in NGC 1275 to an extremely high value of $\sim 35$ in NGC 7469. Interestingly, and probably not surprisingly, some of the highest extinctions we obtained came from those spiral galaxies which we view edge-on.

Our observations do not provide enough resolving power to determine how the $q$-value varies within these distant FIR-luminous galaxies. There is, however, enough resolution to separate galaxy pairs for which $\text{IRAS}$ gives only one flux. It is confirmed that UGC 2369(south), NGC 3110, NGC 6286, UGC 10923(west), NGC 7469, NGC 7541, NGC 7771, and UGC 12915 dominate the FIR flux over their companions. These observations also confirm that the $q$-value for NGC 6286 is unusually low. A new $q = 2.26$ is derived for UGC 12915. The new value confirms that it is the radio bridge and not low FIR flux from the disk of UGC 12915 that causes the low $q$-value for the system.

Our project has developed strategies that will be of use for future missions, in particular SOFIA. The large aperture of SOFIA will immediately provide a factor of 3 improvement in resolution over KAO. New detector arrays being developed for SOFIA instruments (e.g., HAWC—the High Resolution Airborne Wideband Camera) will better sample this diffraction spot. In addition, the higher sensitivity of SOFIA will not only provide sensitivity to the structure at small scales but will also more specifically make available a large number of asteroids for point source and flux calibration.

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