A DIRECT DETECTION OF DUST IN THE OUTER DISKS OF NEARBY GALAXIES

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ABSTRACT

We measure the extent of 100 μm galactic emission in two independent galaxy samples using the IRAS 100 μm Sky Survey images and constrain the distribution of dust at large (≤ 30 kpc) radii. The first sample consists of 90 nearby (v < 6000 km s⁻¹) galaxies from the Third Reference Catalogue of Bright Galaxies with similar angular sizes and absolute luminosities (5 ≤ D₂₅ ≤ 10° and −22.5 ≤ Mᵥ ≤ −18) that are isolated in the 100 μm images. The second sample consists of 24 local galaxies (v < 1500 km s⁻¹, 10° ≤ D₂₅ ≤ 30°). We rescale the 100 μm images of these galaxies using their optical diameters, D₂₅, rotate the images using their optical major-axis position angle, construct the mean and median images, and rebin the final images into polar coordinates to study the 100 μm emission as a function of radius and azimuthal angle. We find that the 100 μm emission extends at least to radii of 33 kpc (2 σ detection) for the typical galaxy in the 5°–10’ sample and to 21 kpc (2 σ detection) in the 10°–30’ sample (H₂ = 75 km s⁻¹ Mpc⁻¹). In both samples, the emission is preferentially elongated along the optical major axis. We fit an exponential to the 100 μm emission along the major axis and measure a scale length of 2.5 ± 0.8 kpc (90% confidence interval). Using a simple model that relates the far-IR emission to the stellar distribution, we examine the range of acceptable dust mass distributions allowed by our data and conclude that the dust is more extended than the starlight.

Key words: dust, extinction — galaxies: spiral — infrared radiation — surveys

1. INTRODUCTION

Of the three principal baryonic components of any galaxy—stars, gas, and dust—the distribution of dust is the least understood. The radial density distribution of the stellar component in disk galaxies falls off exponentially with a scale length ranging from ~1 to 10 kpc (de Jong 1996a, 1996c) out to an abrupt radial cutoff (van der Kruit & Searle 1981a, 1981b, 1982a, 1982b). The radial density distribution of neutral hydrogen is flat (e.g., Shaya & Federman 1987) out to a radial cutoff, while that of molecular gas is generally exponentially decreasing (e.g., Young & Scoville 1991) even though there is evidence for the presence of cold molecular gas at large galactic radii (e.g., Lequeux, Allen, & Guilloteau 1993; Fich, Blitz, & Stark 1989; Wouterloot et al. 1990). These various distributions have been used to study the formation of disks (cf. Fall & Efstathiou 1980; Lin & Pringle 1987), star formation in disks (Kennicutt 1989), and the relation between the neutral hydrogen fraction and the ionizing intergalactic radiation field (Maloney 1993). Does dust trace the stellar or gaseous components (either the atomic or molecular phase)? The resolution of this question may yield insight into past star formation in galactic disks and into the energetics and transport of the interstellar medium (ISM) throughout disks. The goal of this study is to infer the average radial and angular distributions of dust at large radii in galaxies, by measuring the 100 μm emission from ensembles of galaxies.

Existing studies of dust in galaxies rely on one of two physical phenomenae: (1) the extinction of light by dust grains (e.g., Zaritsky 1994; Block et al. 1994; Peletier et al. 1995; de Jong 1996b); and (2) the emission of far-infrared/millimeter light by dust grains (e.g., Rice et al. 1988; Bothun & Rogers 1992; Andreani & Franceschini 1996; Odenwald, Newmark, & Smoot 1997). The application of either approach becomes increasingly difficult at larger radii. By measuring the extinction of background galaxies observed through the halos of two large, nearby spirals, Zaritsky (1994) presented preliminary evidence of dust at radii of ~60 kpc. Studies of the far-infrared (FIR) emission from galaxies have focused on dust within the optically luminous disks of nearby galaxies of large angular extent (Rice et al. 1988; Bothun, Lonsdale, & Rice 1989; Bothun & Rogers 1992; Rice 1993). Bothun & Rogers (1992) detected 100 μm emission out to approximately 30 kpc in six of the 28 galaxies in their sample. However, the signal-to-noise ratio is rather low in these outer regions, and there is limited spatial information. Reliable, general constraints on the distribution of dust beyond ~15 kpc are scarce.

We strive for sensitivity by co-adding the 100 μm images of 115 galaxies drawn from the IRAS Sky Survey Atlas (ISSA; Wheelock 1994) to measure the radial extent, profile, and azimuthal distribution of the thermal dust emission. We choose to work with the longest wavelength IRAS images because we are interested in the distribution of dust at large radii, which is most likely cold (≤ 30 K) and therefore has peak emission at λ ≥ 100 μm. In § 2, we discuss the selection criteria for the sample and control galaxies and describe our algorithm. In § 3, we present the results.
obtained from the two samples. Finally, in § 4 we model the 100 \( \mu m \) emission and present a simple model that constrains the dust distribution.

2. DATA

2.1. Sample Selection

Our measurement of the emission from cold dust in galaxies is based on the combination of 100 \( \mu m \) ISSA images (Wheelock 1994) and basic galactic data from the Third Reference Catalogue of Bright Galaxies (RC3; de Vaucouleurs et al. 1991). We limit our study to Galactic latitudes \( b \gtrsim 15^\circ \) and \( b \lesssim -40^\circ \) to minimize Galactic cirrus contamination and select candidates from the RC3 based solely on their coordinate positions, regardless of other galactic properties such as morphology. Figure 1 shows a \( \sim 20^\circ \times 20^\circ \) section of the 100 \( \mu m \) atlas near \((\alpha, \delta) = (1^h 20^m, 0^\circ)\) or, equivalently, \((l, b) = (139^\circ 5, -61^\circ 6)\). The images have 1.5 pixels. The filamentary features of large angular extent are the result of Galactic cirrus (Low et al. 1984). The numerous small, high surface brightness knots are predominantly galaxies and are typically comparable in size to the point-spread function (PSF) of the survey (FWHM \( \approx 5^\prime \); ISSA).

The most serious difficulty faced by this study is the irregular structure of the Galactic foreground emission. As illustrated in Figure 1, the contamination can be high even at high Galactic latitude. To ensure that the final sample of galaxies do not have close companions and that they lie in quiescent regions of the foreground sky, we identify each candidate on the ISSA images using RC3 coordinates and a gnomonic coordinate projection centered on the central coordinates of our 35\(^\circ\) survey images and apply the following criteria:

1. Centering convergence.—The galaxies’ 100 \( \mu m \) luminosity centroids are calculated using the IRAF CENTER routine.\footnote{IRAF is distributed by the National Optical Astronomical Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.} We reject galaxies with 100 \( \mu m \) centroids that have internal uncertainties greater than 0.45 in either \( x \) or \( y \) (greater than one-third of a pixel), or that have 100 \( \mu m \) centroids that differ by more than 2:25 (\( \sim 0.5 \times \) FWHM of a point source) from the projected coordinates. Typically, galaxies fail these criteria if they have a low signal-to-noise ratio, a close companion, or lie in regions of high cirrus contamination. About 90\% of the original 23,660 possible target galaxies are rejected after applying these criteria.

2. Photometric convergence.—We perform aperture pho-
ometry on the remaining galaxy candidates using the IRAF PHOT routine and apertures with radii from 1.5 to 10.5 spaced by 1.5. We reject any galaxy whose magnitude does not converge, on the grounds that the local background must be strongly affected by cirrus emission. This step excludes \( \sim 6\% \) of the remaining targets.

3. Image edge and bad-pixel contamination.—Galaxies within 52.5 (a distance equal to the region of the extracted subimage used in the analysis) of the image edge are rejected. In addition, the process of mosaicking smaller images to produce the \( \sim 30' \times 30' \) SSA images can create streaks of bad pixels at the interface of the subimages. Any galaxies falling in regions of these bad-pixel streaks are rejected. Because both the shape of the final mosaic images and the initial subimages vary from image to image, this step is done interactively and excludes \( \sim 17\% \) of the remaining galaxies.

4. Multiple identifications.—Any 100 \( \mu m \) source that was associated with multiple optical sources was rejected, excluding \( \sim 9\% \) of the remaining galaxies.

5. Close companion contamination.—To avoid contamination from close companion galaxies, we reject any galaxy with a cataloged companion within 30' projected separation. This cut excludes \( \sim 20\% \) of the remaining targets.

6. Visual inspection.—To ensure that the final galaxy sample is not contaminated by either strong cirrus or close companions not listed in the RC3, we visually inspected each image. Interactively, we only removed 3% of the remaining galaxies. Overall, 95% of the original galaxies are rejected as a result of the above cuts.

This procedure yields a heterogeneous set of isolated galaxies, which spans a wide range of sizes, distances, luminosities, and inclinations. For the addition of galaxy images to be physically meaningful, we must normalize their apparent angular scales and brightness using their isophotal diameters and their central surface brightnesses. In defining the final samples, we want to maximize the number of galaxies to increase the sensitivity yet minimize the range of isophotal diameters and central surface brightness to avoid large scaling factors that greatly magnify the PSF (which could mask an otherwise resolvable detection) and decrease the signal-to-noise ratio. Therefore, we impose two conditions. First, the isophotal diameters of galaxies in any particular sample cannot be scaled by more than a factor of 3. We bin the samples into three groups according to particular sample cannot be scaled by more than a factor of 3.

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The final samples consist of 24 galaxies in the 10'–30'

![Figure 2](image.png)

**Figure 2**—Distributions of recessional velocities and \( R_{25} \) for the 10'–30' sample of 24 galaxies.

**TABLE 1**

| Sample      | Number | \( D_{15} \) (arcmin) | \( V_{rad} \) (km s\(^{-1}\)) | \( \langle V_{rad} \rangle \) (km s\(^{-1}\)) | \( M_B \) (mag) | \( \langle R_{25} \rangle \) (kpc) |
|-------------|--------|------------------------|-------------------------------|--------------------------------------------|----------------|-------------------------------|
| 10'–30'     | 24     | 10–30                  | 0–1600                        | 750                                        | ...            | 18.9                          |
| 5'–10'      | 91     | 5–10                   | 500–3300                      | 1500                                       | 18 to 23       | 18.1                          |
| 2.5'–5'     | 184    | 2.5–5                  | 700–6800                      | 2100                                       | 18 to 23       | 13.6                          |
| Control galaxies | 200 | 0–1.5                  | 1000–16000                    | 5800                                       | 18 to 23       | ...                           |
| Control stars | 30   | ...                    | ...                           | ...                                        | ...            | ...                           |
1. We extract a subimage of $121.5 \times 121.5$ (81 pixels) centered on each galaxy using the 100 $\mu$m galaxy centroid.

2. This subimage is rotated and scaled using IRAF's IMLINTRAN routine and the optical position angle and $D_{25}$ from the RC3, while conserving total flux.

3. We subtract a mean sky value measured in an annulus defined by $30' < R < 52.5'$, where $R$ is the radius from the target galaxy.

4. We normalize the flux, as measured by our aperture photometry, so that the galaxy's central surface brightness is equal to unity.

Upon completion, the resulting images of each galaxy are combined into a mean and median image, applying 10 $\sigma$ clipping to remove spurious pixels. The outer border (width = 10 pixels) of the resulting co-added image is fitted by a plane to remove any large-scale sky variations. The image is then rebinned into polar coordinates, which allows a straightforward comparison of the radial extent of the 100 $\mu$m emission as a function of polar angle (e.g., Fig 7).

Finally, the sky is resubtracted (always a small subtraction, less than 1%) and the central surface brightness is renormalized (always a small division factor, resulting in less than 1% effect). The result of this procedure is an image in polar coordinates that is the sum of 184 galaxies in the 2.5'–5' sample, 91 galaxies in the 5'–10' sample, and 24 galaxies in the 10'–30' sample, from which we measure the shape and extent of the 100 $\mu$m emission.

We do not attempt any correction for galaxy inclination angle. For all but the most nearby, face-on galaxies, the 5' PSF of the images equals or exceeds the galaxies' ISSA minor axes. However, the major difficulty with any attempt at deprojection is the complex background component that cannot be removed on a galaxy-by-galaxy basis. The other option to address this issue, exclusion of lower inclination galaxies, is also not tenable. This option substantially decreases the sample size and our ability to detect emission at large radii. Therefore, we have chosen to apply no inclination correction, but only present quantitative results from data taken along the major axis of the final summed image, which is least affected by inclination.

Most, if not all, of the 100 $\mu$m emission from galaxies in the samples is dominated by emission from the unresolved or marginally resolved inner portions of the disks. Consequently, our ability to detect extended 100 $\mu$m emission is highly dependent on the determination of an accurate 100 $\mu$m PSF. At a distance of 25 Mpc, $D_{25}$ corresponds to 5'. The *IRAS* 100 $\mu$m PSF is $\sim 5'$ on the longest side but is asymmetric and varies spatially across the images and because of survey coverages thus is too complicated to model. We will rely on an empirical determination from two independent sets of unresolved sources.

To determine the PSF in an empirical manner that is entirely consistent with the collection and analysis of our sample, we select two independent sets of unresolved sources: stars detected in all four bands of the *IRAS* Faint Source Survey (Moshir et al. 1989), and compact galaxies ($D_{25} \leq 1.5'$) from the RC3. As long as stars do not have extended structure (such as debris disks or envelopes) then they are truly point sources and, so, are apparently an ideal control set to determine the PSF empirically. Such extended structure is characterized by an IR excess, and therefore we select stars with $F_{12} > F_{60}$, where $F_{12}$ and $F_{60}$ are the fluxes at 12 and 60 $\mu$m, respectively. Unfortunately, there...
are too few stars (30 that survived our selection criteria) to compare with the more numerous 2.5'-5' and 5'-10' samples, and the stars have a much higher central surface brightness than the galaxies, which may be an issue with detector hysteresis. However, because the 10'-30' sample is few in number ($N_{10'-30'} = 24$) and those galaxies in the sample are bright, we use the stars to determine the PSF to use for comparison to this sample. The compact galaxies are generally distant ($V_{rad} = 5789$ km s$^{-1}$) and unresolved ($D_{25} \leq 1.5$). These control galaxies are much more numerous ($N_{con} = 200$) than the stars and have brightness characteristics that are very well matched to the two sets of sample galaxies, 2.5'-5' and 5'-10', with which they are compared. Figure 5 shows the distribution of recessional velocities, $V_{rad}$, and $M_B$ for the control galaxies. As is the case for the sample galaxies, the control galaxies are predominantly of types Sd and earlier (see Fig. 6). This set of control objects results in a conservative estimate of the PSF because the dust emission from these galaxies is not necessarily unresolved. See Table 1 for a summary of the mean properties of the two control samples.

We calculate the PSF using these two control samples and Monte Carlo techniques to reproduce the range of spatial rescalings and rotations applied to the data. Our procedure includes:

1. The extraction of a 121.5' x 121.5' control galaxy subimage, randomly selected from the complete control set;

2. Spatial rescaling and rotation of the control subimage using parameters drawn from a corresponding sample galaxy;

![Fig. 5](image_url)  
Fig. 5.—Same as Fig. 3, but for the control sample of 200 galaxies.

![Fig. 6](image_url)  
Fig. 6.—Distribution of galaxy type, as listed in the RC3, for all three samples of galaxies and the control galaxies.
3. Sky-subtraction and normalization so that the central surface brightness of the control galaxy equals unity, as is done for the sample galaxies.

These steps are repeated until the number of randomly selected control galaxies equals the number of sample galaxies. The control objects are then co-added using the same algorithm as outlined above for the sample galaxies to produce an image of the PSF. For the 2.5–5′ and 5′–10′ samples, we repeat this procedure 20 times to get a mean representation of the PSF and a measurement of the uncertainty in the mean PSF. For the 10′–30′ sample, the number of control stars is comparable to the number of sample galaxies, and thus we only repeat the above Monte Carlo procedure 10 times to derive a corresponding mean PSF.

3. RESULTS

Any 100 μm flux in excess of that expected from a point source is a direct detection of extended emission from galaxies. To determine if excess emission exists, we construct residual images by subtracting the PSF image from the co-added sample image. The residual image for the 10′–30′ sample is presented in Figure 7, where the left and right panels are the residual images before and after rebinning into polar coordinates, respectively. The residual image was produced by combining the sample galaxy images using a median filter. The right panel shows 100 μm emission that is easily visible to a radius of ~1.1R25 ≈ 21 kpc. Also, both panels illustrate that the residual emission is most extended along the optical major axis of the disk, thus indicating that the dust responsible for the 100 μm emission is flattened into a disk.

The radial distribution of the residual 100 μm emission (averaged over 0° ≤ |θ| ≤ 22.5°, where θ is the angle such that 0° is along the disk major axis) for all three samples is shown in Figure 8. The mean PSF has been subtracted from the co-added sample galaxies (combined using a median filter) and also, for comparison, from each individual Monte Carlo realization of the control. Uncertainties in the residual surface brightness profile are calculated from the rms scatter of the various Monte Carlo realizations of the control samples. At the 2σ level, 100 μm emission extends to a radius of 1.1R25 ≈ 21 kpc for the 10′–30′ sample and to 1.3R25 ≈ 25 kpc at the 1σ level (Fig. 8, left). For the 5′–10′ sample, residual 100 μm extended emission is detected to a radius of 1.8R25 ≈ 33 kpc at both the 1σ and 2σ levels (Fig. 8, middle). The 2.5–5′ sample (Fig. 8, right) shows no significant extended emission at any radius. This null detection is consistent with our two previous detections because the apparent angular size of the 100 μm detection in the two nearby samples is not resolvable at the mean distance of the 2.5–5′ sample and thus serves as a check on our method, demonstrating that a spurious detection is not produced by the method. These results are summarized in Table 2. Combination using an average filter produces essentially identical results (at the 2σ level: 1.1R25 ≈ 21 kpc for the 10′–30′ sample and 1.8R25 ≈ 33 kpc for the 5′–10′ sample) and therefore is not shown explicitly. Because the results are the same using either the average or median combination, we are assured that these detections are not the result of one (or

![Figure 7](image_url)
a few) dominant galaxies. Rather, extended 100 µm emission is a typical feature of disk galaxies.

4. DISCUSSION

We now investigate the distribution of the 100 µm emission in more detail and attempt to constrain the distribution of dust. First, we examine the radial shape of the FIR surface brightness profile and compare it with that of the underlying stellar component. Second, we use a simple model to convert the surface brightness profile into a dust mass profile. Finally, we briefly discuss the implications of our derived dust mass distribution.

4.1. 100 µm Surface Brightness Profile

We have detected 100 µm emission at radii of 21 kpc for the 10'–30' sample and 33 kpc for the 5'–10' sample at the 2σ level, but what is the shape of that surface brightness profile? Although the resolution of our data is coarse (half-widths at half-maximum HWHM\(_{10'–30'} \approx 9.5\) kpc and HWHM\(_{5'–10'} \approx 19\) kpc), the pixel scale (1.9 kpc pixel\(^{-1}\) for the 10'–30' sample and 5.7 kpc pixel\(^{-1}\) for the 5'–10' sample) is sufficiently small to provide for several pixels of coverage over the detection. We do not resolve extended emission along the disk's minor axis, and therefore we confine ourselves to parameterizing the major-axis profile. However, we can conclude that the 100 µm emission is confined to within 9.5 kpc of the disk plane for the 10'–30' sample and within 19 kpc for the 5'–10' sample (independent of inclination because these are upper limits).

Along the direction of maximum emission (0° ≤ |θ| ≤ 22°5), we fit an exponential radial profile to the surface brightness, a model for the underlying light distribution, convolved with a Gaussian, a model for the PSF. Because we do not know the effective PSF or the exponential scale length of the 100 µm emission, both the HWHM of the Gaussian and the exponential scale length, \(r_d\), are free parameters. We simultaneously fit the data from both samples to the convolved function by minimizing \(\chi^2\) (and imposing the conditions that HWHM\(_{10'–30'} = 2.0\) HWHM\(_{5'–10'}\) and that the exponential scale lengths be the same). Figure 9 demonstrates our best fit, which is obtained for HWHM\(_{10'–30'} = 0.595R_{25} = 11.0\) kpc and \(r_d = 0.13R_{25} = 2.4\) kpc, with a reduced \(\chi^2 = 2.84\). For the majority of the 100 µm surface brightness profile, the best fit is generally within the 1σ error bars, which are derived from the rms scatter of the mean of the various Monte Carlo realizations of the control samples. More significant deviations occur in the outer regions of the profile, when the flux values approach sky levels (∼\(R_{25}\) for the 10'–30' sample and ∼2\(R_{25}\) for the 5'–10' sample). Although the errors are large, we may be seeing evidence for a second, more extended component at large radius (\(r \gtrsim 25\) kpc).

The task of determining the uncertainties of the parameters is more difficult than that of identifying the best parameters. Although some parameters yield good fits that cannot be rejected at a confidence level greater than 90%, neither model has a reduced \(\chi^2 \sim 1\). Either the model is not entirely representative and there is a nonexponential tail to the dust emission, or the uncertainties are underestimated. We conservatively suggest that \(\chi^2\) is inflated. As a result of details of the polar rebinning procedure, pixels at small radii are not independent [i.e., for small \(r\), one (\(x, y\)) pixel contributes to different (\(r, \theta\)) pixels after rebinning]. Therefore, the calculated rms scatter for pixels at small \(r\) does not fully reflect the uncertainties. To compensate for this effect,
we now renormalize the errors in the following manner: Because the underestimation of uncertainties is more severe at small radii than at large, we renormalize the errors using a factor \( \propto A/R \) and define \( A \) to result in \( \chi^2 = 1.0 \) while fixing the model Gaussian to have \( 0.585R_{25} \leq \text{HWHM}_{10^\circ-30^\circ} \leq 0.595R_{25} \), drawn from the best fit (the IPAC-estimated PSF has \( \text{HWHM}_{10^\circ-30^\circ} \sim 0.50R_{25} \)). Using the renormalized errors and fixing the range of the HWHM, we again simultaneously fit the models to the data from both samples and find the following parameter range acceptable within the 90% confidence level: \( 0.09R_{25} \leq r_d \leq 0.18R_{25} \), or 1.7 kpc \( \leq r_d \leq 3.3 \) kpc.

One important result that may be casually overlooked is the significance of simultaneously fitting the data from both samples to the same exponential. One might naively expect that dust should be detected in either sample out to the same radius, particularly since, as pointed out previously, the galaxies in these two samples do appear to be of the same type (\( \langle R_{25} \rangle \sim 18.5 \) kpc for both samples). However, because of the differences in sample size, the mean distance of galaxies in the two samples, and the effect of the PSF on samples of different angular size, the sensitivities are not the same. Separate fits to the two samples yield the 90% confidence parameter ranges listed in Table 3. The range of acceptable parameter space allowed by fitting the two samples separately is consistent with that allowed by simultaneously fitting both samples and with each other.

How does our derived 100 \( \mu \)m emission scale length compare with that of the stellar component in a typical disk galaxy? The most recent and complete study of stellar disks is that of de Jong (1996a, 1996c), who uses near-infrared and optical broadband surface photometry of 86 face-on, disk-dominated galaxies to investigate the distribution of disk and bulge parameters. Because \( K \)-band light is less affected by dust obscuration than is \( B \)-band light, we choose to compare our result with the distribution of \( K \) scale lengths that range from \( \sim 1 \) to 10 kpc, with a median of \( r_d^K = 3.8 \) kpc, and an rms dispersion of 2.4 kpc (for \( H_0 = 75 \) km s\(^{-1}\) Mpc\(^{-1}\)).

### Table 3

**Best-Fit* Parameters for 100 Micron Surface Brightness Profile Fitting**

| Sample             | HWHM\(_{10^\circ-30^\circ}\) | \( r_d \) |
|--------------------|-------------------------------|------------|
| 10'-30'            | 0.520R\(_{25}\)-0.650R\(_{25}\) | 0.09R\(_{25}\)-0.20R\(_{25}\) |
|                    | 9.6 kpc-12.0 kpc              | 0.9 kpc-3.7 kpc |
| 5'-10'             | 0.565R\(_{25}\)-0.610R\(_{25}\) | 0.05R\(_{25}\)-0.20R\(_{25}\) |
|                    | 10.5 kpc-11.3 kpc            | 0.9 kpc-3.7 kpc |
| Simultaneous fits to both samples | 0.585R\(_{25}\)-0.595R\(_{25}\) | 0.09R\(_{25}\)-0.18R\(_{25}\) |
|                    | 10.8 kpc-11.0 kpc            | 1.7 kpc-3.3 kpc |

* Within 90% confidence level.

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**Fig. 9.**—Simultaneous best fit to the 100 \( \mu \)m surface brightness profiles of the 10'-30' sample (left) and the 5'-10' sample (right), before renormalizing the errors. The surface brightness profiles are modeled by an exponential convolved with a Gaussian distribution (see text for details). The 1 \( \sigma \) error bars plotted are derived from the rms scatter of the mean of the various Monte Carlo realizations of the control samples.
However, the distribution of scale lengths is a positive definite quantity with a significant high-end tail that is not described by a Gaussian distribution. Therefore, the median is biased to a larger value than the peak of the distribution, which is quite broad and is in the range ~2–4 kpc (40% of the galaxies have scale lengths in this range). This range overlaps the 2.5 ± 0.8 kpc range of 100 μm scale lengths that we measured. Because de Jong finds no correlation of scale length with galaxy type, any differences in the distribution of galaxy type between the optical study and our samples is unimportant. We conclude that the derived 100 μm scale length is most likely not much larger than that of the underlying old stellar component and is consistent with being equivalent to or up to a factor of 2 smaller than that of the stellar distribution.

4.2. A Simple Model for the Dust Distribution

The characteristic scale length of the 100 μm emission derived in § 4.1 can be used, in conjunction with simple modeling, to place a limit on the global dust mass distribution. Because we have data in a single passband with poor spatial resolution, we follow the procedure of Bothun & Rogers (1992), who use a one-component model (a single blackbody with characteristic temperature) to describe the FIR emission from dust, based on 60 μm and 100 μm IRAS images. The one-component assumption is questionable because of the different temperature dust components needed to fit observed FIR spectral energy distributions. Some find that multicomponent models are needed to explain their FIR observations (e.g., Helou 1986; Rowan-Robinson & Crawford 1989; Andreani & Franceschini 1996), while others concur with Bothun & Rogers (1992) and find that their FIR spectra can be well fitted by a single-component model (e.g., Sodroski et al. 1994; Clements, Andreani, & Chase 1993; Odenwald et al. 1996). Using DIRBE all-sky data, Sodroski et al. (1994) showed that a ubiquitous FIR component can be detected as a single component at 60 μm < λ < 240 μm with 17 K < T_d < 22 K that is closely associated with the FIR cirruses discovered by IRAS at 100 μm. Studies of IR-selected galaxies find that the galaxies’ continua are consistent with a single-component model with 25 K ≲ T_d ≲ 35 K and a peak emission near 100 μm (Clements et al. 1993; Odenwald et al. 1996). While dust certainly exists at a variety of temperatures, we use a simple one-component model because of the limited temperature information provided by our single-band data, and the evidence that the FIR continua of the 100 μm-emitting dust is well fitted by a single-temperature blackbody in the range 20 K ≲ T_d ≲ 35 K. Subsequent observations at millimeter wavelengths will be necessary to test this assumption.

Bothun & Rogers (1992) model the 100 μm emission using an isothermal dust slab at a dust temperature, T_d, that is optically thin to FIR emission. They assume that within each region of the disk sampled by a pixel, radiative equilibrium exists between the interstellar radiation field (ISRF) and the dust grains, and also that the ISRF, represented by mean intensity, J_0, is uniform over the region. They derive the following relationship between f_ν, the observed flux density in an IRAS passband with effective frequency ν, and the integrated mean intensity J:

\[ f_\nu \propto \mathcal{F}_\nu (T_d) \tau_J J, \quad (1) \]

where \( \tau_J \) is the mean-intensity-weighted optical depth of the dust and \( \mathcal{F}_\nu \) is the fraction of the total emission contained within the IRAS band. For a power-law dust emissivity law that is proportional to \( \nu^q \), \( \mathcal{F}_\nu \) can be expressed as

\[ \mathcal{F}_\nu = \frac{\int_0^\infty x^{3+q} e^x dx}{\Gamma(4+p)\Gamma(4+p)} \]

where \( x = \nu / k T_d \), \( R_\nu \) is the system response for the band that is tabulated in the IRAS Explanatory Supplement, and \( \Gamma \) and \( \zeta \) are the gamma and Riemann zeta functions.

Because \( \tau \) is proportional to mass in the optically thin regime, we can use the above equations to trace dust mass as a function of radius if we know the dust temperature profile, the 100 μm light profile, and the integrated mean intensity profile of the ISRF. The radial profile of the dust mass distribution can be derived without needing to derive the various coefficients, which are difficult to determine empirically. We assume that

\[ J \propto \exp (-r/r_s), \quad (3) \]

where \( r \) is the radius and \( r_s \) is the scale length of the stellar component. We determined above that the 100 μm emission is also described by an exponential, and thus

\[ f_\nu \propto \exp (-r/r_s), \quad (4) \]

where \( r_s \) is the 100 μm emission scale length. The only term in these equations that depends on the dust temperature is \( \mathcal{F}_\nu \). Bothun & Rogers (1992), using 60 and 100 μm images for 28 nearby galaxies, found that the dust temperature declines radially as a result of the exponentially declining ISRF. These authors modeled the temperature profile with an exponential,

\[ T_d \propto \exp (-r/r_s), \quad (5) \]

which, for a limited range of scale lengths, can be approximated by a drop of 3 K for every optical scale length (Bothun & Rogers 1992). This temperature profile is consistent with their data out to a radius of ~3 optical scale lengths, where the temperatures converge to a near-constant value of ~28 K (Bothun & Rogers 1992). Therefore, we use the exponential temperature gradient, normalized to produce \( T_0 = 34.9 \) K at 1 optical scale length and converging to a constant temperature of 28 K for \( r > 3r_s \).

We can now solve for the dust distribution once we adopt values for the 100 μm emission scale length, \( r_s \), and the scale length of the stellar component, \( r_s \). For \( r_s \), we choose the mean of the two best-fit values, \( r_s = 2.5 \) kpc. As discussed above, the 100 μm scale length could be equal or up to a factor of ~2 smaller than the stellar scale length. Thus, we investigate the regime \( 0.5 \leq r_s / r_s \leq 1 \). When \( r_s / r_s = 1 \), the model predicts a slight fall in the dust mass distribution in the inner regions of the galaxy (because of the radial temperature gradient), and then the dust mass distribution flattens out when the temperature converges to a constant. In the absence of a temperature gradient, the distribution is flat at all radii. This result occurs because equation (1) simplifies to \( \tau \propto 1/\mathcal{F}_\nu (T_0) \) for equal stellar and dust emission scale lengths. If the temperature is constant with radius, then \( \mathcal{F}_\nu \) is constant, and \( \tau \) is independent of radius. For \( 0.5 \leq r_s / r_s < 1 \), an exponentially declining dust mass with radius is predicted, with the dust being less centrally concentrated than the stars. As \( r_s / r_s \) decreases, the dust mass scale length decreases until it equals the stellar emission scale length for \( r_s / r_s = 0.5 \).
A flat or slowly declining exponential radial dust distribution is consistent with the findings from optical studies. De Jong (1996b) studied the optical and infrared color profiles of 86 face-on disk-dominated galaxies using models of well-mixed stars and dust that include both scattering and absorption. He found that high central optical depths and long dust scale lengths best reproduced the observed color gradients. However, he cautions that a realistic dust distribution alone cannot adequately account for the observed gradients and that stellar population characteristics, namely, age and metallicity gradients, need to be incorporated. Peletier et al. (1995) also studied spiral galaxies in the optical and infrared using models of smoothly distributed dust and stars that only included absorption, but he also concluded that $r_d/r_s > 1$. However, when they included scattering and clumpiness in the dust models, $r_d/r_s \geq 1$ yielded acceptable solutions.

### 4.3. Implications of the Dust Mass Distribution

How does the dust distribution compare to other galaxy components? Neutral hydrogen has a radially flat distribution (Shaya & Federman 1987), while molecular gas appears to decline exponentially (e.g., Young & Scoville 1991). Because our data cannot distinguish between a flat or exponentially declining distribution of dust, we will discuss both cases. Some authors find a good correlation between FIR luminosities and the distribution of molecular gas (e.g., Devereux & Young 1990a, 1990b, 1992, 1993; Tinney et al. 1990; Sanders, Scoville, & Soifer 1991; Downes, Solomon, & Radford 1993; Sage 1993). Devereux & Young (1990a, 1990b, 1992, 1993) studied the origin of the FIR luminosity in IR-luminous spiral galaxies and concluded that FIR luminosity is an excellent indicator of star formation, being well correlated with $H_2$ luminosity and the surface density of $H_2$ (as inferred from CO observations) and poorly correlated with the surface density of H I. These authors claim that their observed FIR luminosities are the result of the reradiation by warm dust of UV flux from young OB stars in H II regions and, therefore, the dust exponentially declines with radius as do the stellar and molecular components.

Others provide evidence for a second, cooler, more diffuse cirrus-type component, which is associated with the H I rather than star-forming regions and excited by the ISRF from old disk stars. Using a model that includes both components, Lonsdale-Persson & Helou (1987) have calculated that cirrus-type emission can account for up to between 50% and 70% of the total FIR emission from a median spiral galaxy, and subsequent observations have supported their claim (Walterbos & Schr"{o}ering 1987; Rice et al. 1990; Sauvage & Thuan 1992; Xu & Helou 1996). Furthermore, Sauvage & Thuan (1992) observationally determined that the fractional contribution of cirrus-type emission to the total FIR of spiral galaxies is a function of type: ~3% for Sdm galaxies, increasing to ~70% for Sc galaxies, and reaching as high as ~86% for Sa galaxies. When normal spiral galaxies (i.e., not ultraluminous IRAS galaxies or active galaxies) are studied, the contribution from the cirrus component becomes important, and non-negligible correlations between cold dust and H I are found, although cold dust is better correlated with the total gas content ($H_1 + H_2$) than with either phase separately (e.g., Knapp, Helou, & Stark 1987; Andreani, Casoli, & Gerin 1995; Xu & Helou 1996). Xu & Helou (1996) studied the diffuse component of the FIR emission of M31 by removing FIR emission associated with H II regions and found a close association of the diffuse cirrus-type component with H I, while a poor correlation was found with $H_2$. It is interesting that these authors calculate the radial behavior of the V-band optical depth, $\tau_V$, and find that the overall distribution of $\tau_V$ is rather flat out to a radius of $\sim 14$ kpc.

Because the galaxies in our samples are predominantly of type Sc and earlier, we expect the cirrus component, rather than the dust component associated with H II regions, to be the main contributor to the FIR emission. However, a number of authors have demonstrated that IRAS is not very sensitive to emission by cold dust and that the emission from large amounts of cold dust can easily be dominated by emission from a small amount of warm dust (e.g., Bothun & Rogers 1992; Sage 1993; Block et al. 1994). In reality, the 100 $\mu$m-emitting dust detected in our sample is probably associated, at some level, with both the molecular and atomic gas phases. While our assumed dust temperature of $\sim 30$ K is similar to dust temperatures derived for samples of nearby spiral galaxies (e.g., Young et al. 1986; Walterbos & Schr"{o}ering 1987; Jura 1986; Bothun & Rogers 1992), this is not the characteristic temperature of either H II regions, which are hotter, or the H I ISM, which is typically colder. Our assumed dust temperature was derived by Bothun & Rogers (1992) using a single-temperature model, based on 60 $\mu$m and 100 $\mu$m data with very coarse resolution where each pixel samples a wide range of local heating conditions and consequently is probably an average of the temperatures of the two contributing components. Therefore, although our data do not allow us to differentiate between a flat and exponentially declining distribution of dust, the 100 $\mu$m emission measured in our sample almost assuredly originates from both warm dust residing in H II regions and associated with the exponentially declining molecular gas and also from the cooler, cirrus component associated with the flatly distributed neutral hydrogen.

Ultimately, we would like to know the radial extent of the dust layer. In particular, does it have a cutoff at some radius? Unfortunately, our current data do not allow us to answer this question, but we can use them to place a lower limit on that cutoff radius. We have detected 100 $\mu$m emission from dust out to a radius of 33 kpc (with $\geq 2 \sigma$ confidence). This is a lower limit to the cutoff radius and large amounts of cold dust at larger radii could exist. We can compare this limit with the known edges of the stellar (e.g., van der Kruit & Searle 1981a, 1981b, 1982a, 1982b) and neutral hydrogen (e.g., Corbelli, Schneider, & Salpeter 1989; Corbelli & Salpeter 1993; Bland-Hawthorn, Freeman, & Quinn 1997) disks. Van der Kruit & Searle (1982a) found that all of the stellar disks in their sample of eight galaxies have a sharp edge at 4–5 radial scale lengths, or 14–25 kpc, with an average value of 17 kpc. Neutral hydrogen disks also have a sharp boundary, although at radii beyond the edge of the stellar disk. For example, galaxies in the Sculptor Group have observed H I disks that extend to $\sim 1.2R_{25} \sim 23$ kpc (Bland-Hawthorn, Freeman, & Quinn 1997). Few galaxies have H I disks that extend farther to $\sim 2R_{25} \sim 38$ kpc (Bland-Hawthorn, Veilleux, & Carignan 1997; Bland-Hawthorn et al. 1997). The radial edge of our 100 $\mu$m detection, at a radius of 33 kpc, is beyond 4–5 stellar scale lengths and, therefore, is beyond the edge of the stellar disk. We do not observe FIR emission beyond the nominal edge of H I disks, although because our
If dust is produced by stars, how can dust be found outside the stellar disk? One can speculate that it is primordial, i.e., that it formed early in the process of galaxy formation and then settled into a disk similarly to the H I, that galactic fountains and plumes of gas and dust ejected by supernovae into the ISM pollute the outer galaxy, or that some disk stars exist at these large radii. Models of galactic fountains (e.g., Corbelli & Salpeter 1988) show that some of the hot material ejected by violent supernovae can rise many kiloparsecs into the halo and then radiatively cool and fall back toward the outer part of the galactic plane at distances $\geq 20$ kpc. A similar, but less energetic, mechanism for ejecting dust into the ISM involves radiation pressure produced by clusters of young OB stars. Models of these dusty chimneys by Ferrara (1995) show that some dust particles can attain rather high velocities ($\sim 100$ km s$^{-1}$) and reach distances of $\sim 3$ kpc above the disk plane. However, the majority of the dust particles’ motion is in a direction perpendicular, rather than parallel, to the plane of the disk. The redistribution of dust particles in Ferrara’s models predicts a flattened dust distribution, which is consistent with our work (see Fig. 7). Last, although stellar disks are observed to truncate sharply, there is observational evidence for massive star formation in the outer regions of galactic disks. Hodge, Lee, & Mateo (1988) and Davidge (1993) found blue stars in two different fields in the outer disk ($\sim 20$ kpc) of M31. If these findings are representative of spiral galaxies, then there is at least some star formation at the very edge of stellar disks that could contribute dust at large radii. Therefore, there are several avenues that need to be more fully explored to determine the mechanism involved in getting dust to $r \sim 30$ kpc.

5. SUMMARY

Using 100 $\mu$m ISSA images and data from the RC3, we co-add the flux from 299 galaxies and investigate the radial and azimuthal distribution of 100 $\mu$m emission from dust in ensembles of galaxies. The galaxies are divided into three samples (where $N$ is the number of galaxies) according to their optical isophotal diameter, $D_{25;N}$: (1) $2.5 \leq D_{25;N} \leq 5.0$ ($N_2\leq5\leq184$), (2) $5.0 \leq D_{25;N} \leq 10.0$ ($N_5\leq10\leq91$), and (3) $10.0 \leq D_{25;N} \leq 30.0$ ($N_{10}\leq30\leq24$). We find the following:

1. The 100 $\mu$m emission extends out to radii of 33 kpc at the 2 $\sigma$ or greater confidence level for the $5'\leq10'$ sample and to 21 kpc for the $10'\sim10'$ sample (no extended emission is seen beyond the PSF for the $2.5'\leq10'$ sample).

2. The 100 $\mu$m emission from both the $5'\sim10'$ and $10'\sim30'$ sample is preferentially elongated along the major axis of the disk, thus confirming the validity of the detections and demonstrating that 100 $\mu$m-emitting dust is flattened into the disk.

3. The 100 $\mu$m surface brightness profiles from both samples can be well fitted with an exponential with a dust emission scale length of $\sim 2.5 \pm 0.8$ kpc, but there is evidence for a second, more extended emission component.

4. A model of the 100 $\mu$m emission from an isothermal dust slab at a temperature, $T_d$, that is optically thin to emission can be used to model our data (cf. Bothun & Rogers 1992). Because our data do not allow us to calculate dust temperatures, we adopt the dust temperature gradient derived by Bothun & Rogers (1992), which can be approximated by a drop of 3 K for every optical scale length, $r$, and is normalized by $T_d = 34.9$ K at 1 optical scale length and converges to a near-constant value of $\sim 28$ K for $r > 3r_d$. Using this model, we examine the range of acceptable dust mass distributions allowed by our data and find that the dust is less concentrated than the stars, with either a flat or slowly declining exponential distribution.

We have presented evidence for dust well beyond the stellar disk but have been unable to conclude whether dust exists beyond the extent of the H I distribution. Such dust, if present, should be quite cold ($\leq 10$ K) and difficult to detect with IRAS observations, despite the possible evidence of a second component in our data. The future of this field relies on longer wavelength observations. Preliminary detections of dust at large radii using 200 $\mu$m observations have recently been presented by Alton et al. (1998). We await further results from such observations.

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