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1.25-mm Observations of Luminous Infrared Galaxies

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ABSTRACT. Measurements at a wavelength of 1.25 mm have been obtained for 17 *IRAS* galaxies selected on the basis of high far-infrared luminosity. These measurements are used to estimate the lower and upper limits to the mass of cold dust in infrared galaxies. As a lower limit on dust mass, *all of the galaxies can be successfully modeled without invoking any dust colder than the dust responsible for the 60 and 100 μm emission that was detected by IRAS.* As an upper limit, it is possible that the dust mass in a number of the galaxies may actually be dominated by cold dust. This large difference between the lower and upper limits is due primarily to uncertainty in the long-wavelength absorption efficiency of the astrophysical dust grains.

1. INTRODUCTION

The infrared emission from most galaxies is thought to be dominated by thermal emission from dust grains at wavelengths between a few micrometers and roughly 1 mm, and hence galaxies with very high far-infrared luminosities, L_{IR}, can be inferred to contain significant quantities of dust. For such galaxies, an understanding of the nature and distribution of the dust is clearly of critical importance.

Observations as 12, 25, 60, and 100 μm for a large number of infrared-luminous galaxies have been available for several years through the *IRAS* survey data. Measurements of galaxies at wavelengths longer than 100 μm, however, are comparatively rare. Since the steady-state temperature of a dust grain in the quiescent interstellar medium of a galaxy is expected to be only 10–20 K (see, e.g., Draine and Lee 1984), implying a peak in the thermal emission curve at a wavelength of several hundred micrometers, an important question is whether or not such galaxies contain significant quantities of very cold dust—dust which is too cold to have made a significant contribution to the flux measured by *IRAS*. Chini et al. (1986) argued that such dust was necessary to explain their 1.3 mm measurements of 26 infrared-selected galaxies, whereas Eales et al. (1989), on the basis of 350–1100 μm measurements of 11 *IRAS* galaxies, found that, although cold dust could not be ruled out as a component in such galaxies, the energy distributions could also be satisfactorily modeled without it. In an effort to address this issue, we present measurements at a wavelength of 1.25 mm of 17 galaxies selected from the *IRAS* database and characterized by unusually high far-infrared luminosities. The results are then used to obtain lower and upper limits to the mass of very cold dust in infrared-luminous galaxies. In addition, the results are combined with previous empirical studies and theoretical considerations to estimate the probable long-wavelength form of the absorption efficiency of astrophysical dust grains.

2. THE SAMPLE AND OBSERVATIONS

The 17 galaxies observed here are listed in Table 1. All of the galaxies were selected primarily on the basis of expected detectability at 1.25 mm, so that the sample of galaxies in Table 1 is not complete in any sense. However, with the exception of NGC 1143/4, all of the galaxies are members of the *IRAS* bright galaxy (BG) sample, a complete, flux-limited sample of 313 galaxies with 60 μm flux densities f_ν (60 μm)$\geqslant$5.24 Jy developed by Soifer et al. (1989; NGC 1143/4 was not included in the BG sample because its 60 μm flux density is only 5.06 Jy). Furthermore, since the intent of the current analysis is primarily to study galaxies with high infrared luminosities, most of the galaxies in Table 1 have $L_{IR} \geqslant 10^{11} L_\odot$; however, three lower-luminosity galaxies are also included simply because they were easily observable at the time the measurements were made. The criterion of high luminosity implies higher radiation fields and therefore higher far-infrared color temperatures as compared to those found in lower-luminosity galaxies (Soifer and Neugebauer 1991).

The measurements at 1.25 mm were made in 1988 May and September at the Caltech Submillimeter Observatory on Mauna Kea; a beam 30″ in diameter (FWHM) was used. The CSO continuum radiometer is a single-element ^{3}He-cooled silicon bolometer. For the 1.25 mm atmospheric window, the focal plane aperture is defined by an $f/4$ Winston cone (Harper et al. 1976) with an entrance aperture of 30″ and an exit aperture of 0.75 mm. This exit aperture provides a steep long-wavelength cutoff to the bandpass at 1.8 mm. The short-wavelength cut-on is determined by a four-layer, capacitative-grid low-pass interference filter (Whitcomb and Keene 1980) cooled to 4 K by the ^{4}He bath, with two thin ($\lambda/2$) fluorogold (Muehlner and Weiss 1973) and black polyethylene short-wavelength blocking filters, one at 4 K and one at 77 K. Spatial modulation of the sky was provided by a reimaging aperture-plane chopper mounted at the Cassegrain focus. Calibration was achieved by assuming the brightness temperature of Uranus and Mars to be 100 and 235 K, respectively.

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TABLE 1
1.25-mm Observations

NAME	$\mathrm{LOG}[L_{IR}/L_{\odot}]^a$	$f_\nu(\lambda)(Jy)^b$ 12 μm	25 μm	60 μm	100 μm	1.25 *mm*	T^c_β	β^c	T^d_{IRAS}
NGC 337	10.11	0.40	0.75	9.33	19.18	<0.024	<33.0	>1.7	29.4 ± 1.8
MCG-03-04-014	11.58	0.47	0.88	6.76	10.20	0.027 ± .009	37.1 ± 2.9	1.3	32.5 ± 2.2
NGC 958	11.13	0.59	0.95	5.90	14.99	0.034 ± .007	29.3 ± 1.8	1.6	27.6 ± 1.6
NGC 1055	10.17	2.20	2.89	23.27	60.09	0.073 ± .010	27.5 ± 1.5	2.0	27.5 ± 1.5
NGC 1143/4	11.41	0.27	0.58	5.06	11.45	0.038 ± .008	31.4 ± 2.1	1.4	28.5 ± 1.7
UGC 2982	11.15	0.57	0.86	8.70	17.32	0.047 ± .008	32.2 ± 2.2	1.5	29.7 ± 1.9
UGC 5101	12.01	0.26	1.08	13.03	21.25	<0.036	<38.2	>1.4	31.7 ± 2.1
NGC 3110	11.22	0.58	1.10	11.68	23.16	0.048 ± .013	32.3 ± 2.2	1.5	29.7 ± 1.8
NGC 3690	11.90	3.90	24.14	121.64	122.45	0.095 ± .011	40.3 ± 3.5	1.7	37.8 ± 3.1
Mrk 231	12.52	1.93	8.80	35.40	32.28	0.029 ± .008	44.2 ± 4.3	1.5	39.4 ± 3.4
Mrk 273	12.14	0.23	2.30	22.09	22.44	<0.063	<55.0	>0.9	37.7 ± 3.0
Zw 049.057	11.07	<0.08	0.93	21.06	29.88	0.048 ± .011	36.5 ± 2.8	1.5	33.2 ± 2.3
Arp 220	12.19	0.64	7.92	103.33	113.95	0.226 ± .010	42.5 ± 4.0	1.3	36.5 ± 2.9
NGC 6286	11.32	0.50	0.64	9.87	22.01	0.040 ± .009	30.1 ± 1.9	1.7	28.7 ± 2.2
NGC 7469	11.59	1.60	5.84	27.68	34.91	<0.033	<41.7	>1.5	34.7 ± 2.5
NGC 7541	10.95	1.49	1.99	20.59	40.63	0.067 ± .008	31.3 ± 2.1	1.7	29.8 ± 1.9
NGC 7771	11.34	0.87	2.18	20.46	37.42	0.070 ± .008	32.7 ± 2.3	1.6	30.5 ± 2.0

[a] The far-infrared luminosity from Carico *et al.* (1988), when available, or Soifer (unpublished).

[b] The 12 μm, 25 μm, 60 μm, and 100 μm flux densities are from Soifer *et al.* (1989).

[c] The temperature, T_β, and absorption efficiency spectral index, β, required to fit a single-temperature thermal emission curve, $f_\nu(\lambda) \propto \beta_\nu(\lambda,T)\lambda^{-\beta}$, through the 60 μm, 100 μm, and 1.25 mm data points simultaneously. The uncertainties in T_β are based on uncertainties of ±10% in the *IRAS* data. The uncertainties in the values of β are all roughly ±0.1.

[d] The temperature required for a single-temperature fit through the *IRAS* 60 μm and 100 μm flux densities, for an absorption efficiency spectral index $\beta = 2$. The uncertainties are based on uncertainties in the *IRAS* data of ±10%.

The *IRAS* measurements at 12, 25, 60, and 100 μm are from Soifer et al. (1989).

3. RESULTS AND DISCUSSION

In the following discussion (Sec. 3.1), the 1.25 mm measurements are presented and compared to the measurements of Chini et al. (1986) and Eales et al. (1989; see Sec. 1). The measurements are then used to obtain lower (Sec. 3.2) and upper (Sec. 3.3) limits to the mass of cold dust in infrared-bright galaxies. These results are also used to provide constraints on the long-wavelength absorption efficiency of dust grains which are consistent with current theoretical and empirical considerations.

3.1. The 1.25-mm Data

The results of the 1.25 mm measurements of 17 galaxies from the BG sample are presented in Table 1, along with the *IRAS* data for each source from Soifer et al. (1989). The data are shown graphically in Fig. 1, which includes single-temperature thermal emission curves, $f_\nu(\lambda) \propto Q(\lambda)B_\nu(\lambda,T)$, where $B_\nu(\lambda,T)$ is the Planck function, for an absorption efficiency $Q(\lambda) \propto \lambda^{-\beta}$, with $\beta=2$ (*solid line*) and $\beta=1$ (*dashed line*); the curves are fit to the 60 and 100 μm data points for each source. These curves represent the limits for β given by most models of the long-wavelength emissivity of interstellar dust grains (e.g., Bohren and Huffman 1983). It is seen that the 1.25 mm flux densities fall on or between single-temperature curves for $\beta=1$ and $\beta=2$ for all of the galaxies that were detected at that wavelength.

In Fig. 2, a comparison is shown between the measurements from Table 1 and those presented by Chini et al. (1986) using a 90″ beam and Eales et al. (1989) using beams of 63″–104″. The continua of each of the galaxies were normalized to 100 Jy at 100 μm and then the mean flux density for the appropriate sample of galaxies was plotted. The "error bar" indicates the range of normalized flux densities for the sample at that wavelength. (Note that the error bars do *not* relate to the uncertainties in the measurements of individual galaxies; no attempt has been made to include such uncertainties.) The squares at the *IRAS* wavelengths and at 1.25 mm are the flux densities for the galaxies in the current sample; the circles at 350 and 450 μm represent the sample of eight and five galaxies, respectively, detected by Eales et al.; the triangle at 1300 μm is from the sample of 17 galaxies detected by Chini et al. It should be noted that there is very little overlap between the galaxies reported in the current sample and those reported by Eales et al. and Chini et al. The curve in Fig. 2 is the energy distribution for 33 K emission with $Q(\lambda) \propto \lambda^{-2}$, appropriate for a single-temperature fit to the 60 and 100 μm points in the figure.

It is readily seen that the data from Eales et al. (1989) agree well with the measurements presented herein. Although their samples were quite small, diluting somewhat any statistical significance, it is worth noting that, even

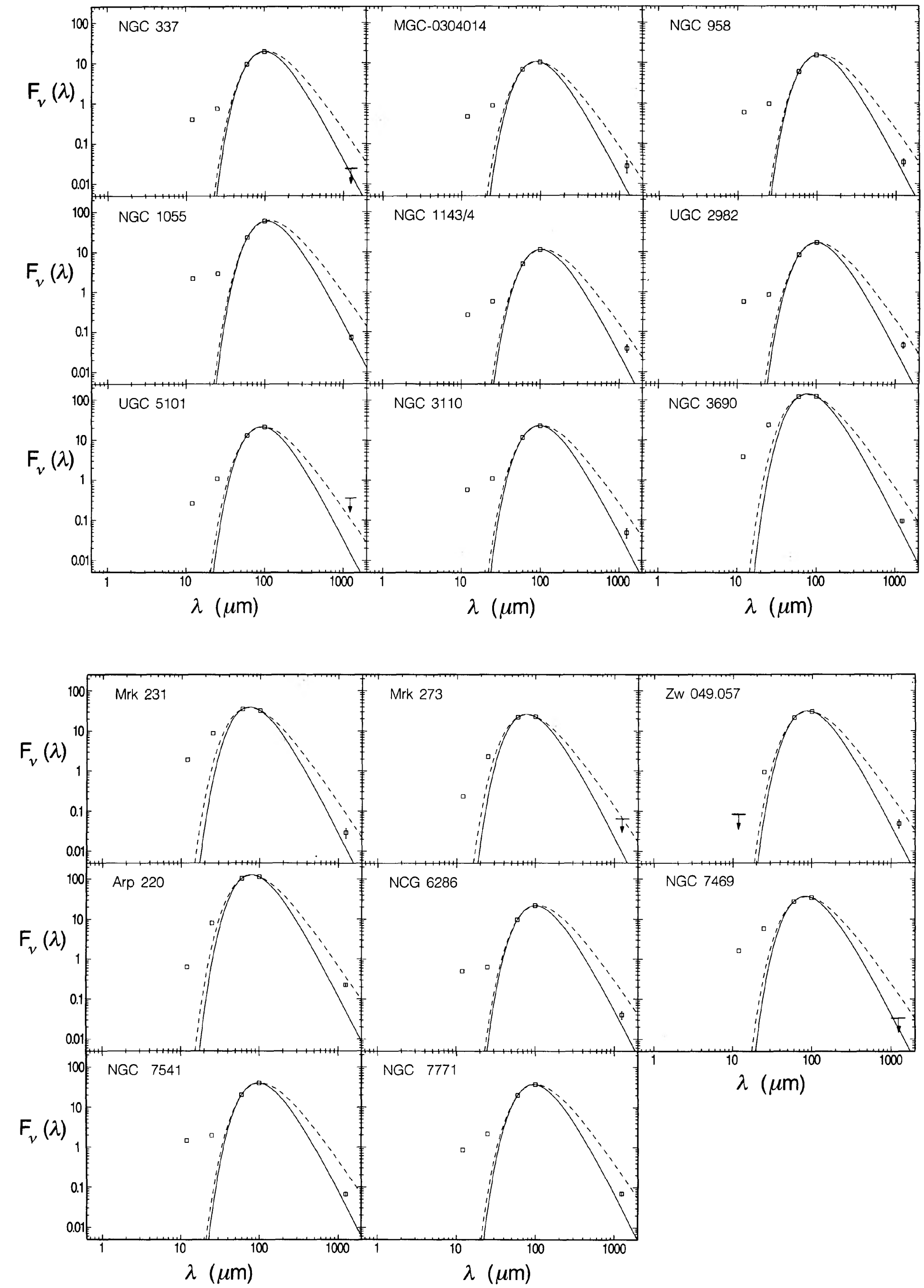

FIG. 1—Far-infrared energy distributions for the galaxies in Table 1. Single-temperature thermal emission curves are shown for an absorption efficiency $Q(\lambda) \propto \lambda^{-\beta}$, with $\beta=2$ (*solid line*) and $\beta=1$ (*dashed line*); the curves are fit to the 60 and 100 μm data points for each source. The *IRAS* data at 12, 25, 60, and 100 μm are from Soifer et al. (1989).

with a beam diameter of 104″, the consistency of the 350 and 450 μm flux densities with the 1.25 mm data presented here provides no evidence that our 30″ beam missed any significant fraction of the emission at longer wavelengths (see Sec. 3.2). In contrast, the results of Chini et al. (1986) do not fit the current sample, the measurements being larger, on average, by a factor of 20–30. We have no explanation for this discrepancy, but point out that Eales et al. also remarked on the discrepancy between their 350 μm measurements and the Chini et al. measurements.

3.2 The Lower Limit to the Mass of Cold Dust

It is clear from Table 1 and Fig. 1 that the measured flux densities at 1.25 mm are inconsistent with an absorp-

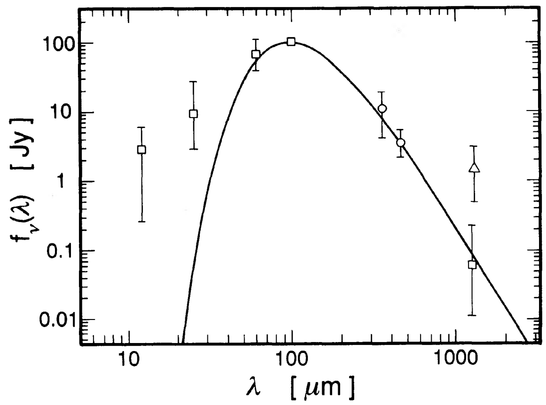

FIG. 2—A comparison between the measurements from Table 1 and those presented by Eales et al. (1989) and Chini et al. (1986). The squares at the *IRAS* wavelengths and at 1.25 mm are the (normalized) mean flux densities for the galaxies in the current sample; the circles at 350 and 450 μm are from Eales et al.; the triangle at 1300 μm is from Chini et al. (See the text for a description of the normalization.)

tion efficiency $Q(\lambda) \propto \lambda^{-1}$ for all of the galaxies that were detected at that wavelength. Values of β, where $Q(\lambda) \propto \lambda^{-\beta}$, required for a single-temperature fit to the 60 μm, 100 μm, and 1.25 mm flux densities are given in Table 1 (along with the corresponding temperatures T_β), and their distribution is shown by the histogram in Fig. 3. These temperatures must be regarded as upper limits to the "mean" dust temperature since the 60 μm flux from galaxies can contain a considerable contribution from nonthermal PAH emission (see, e.g., Desert et al. 1990). This means that the derived grain absorption efficiency index will in general be greater than that derived here.

Before any conclusions can be drawn from these results, possible beam size effects must be considered due to the use of a relatively small 30″ beam diameter for the 1.25 mm measurements, in comparison to the 1–5-arcmin size of the *IRAS* detectors (see the *IRAS Explanatory Supplement* 1988). None of these sources were significantly resolved in the *IRAS* data (Soifer et al. 1989) at 60 and 100 μm, placing limits of $\lesssim 1'$ on the infrared sizes. Radio maps at 1.49 GHz ($\lambda = 20$ cm) of the entire BG sample have been presented by Condon et al. (1990), and the strong correlation between the radio and infrared flux (Helou et al. 1985; de Jong et al. 1985; Condon and Broderick 1988) argues that the emitting regions are of similar sizes. Indeed Bicay and Helou (1990) find that the radio sizes of spiral galaxies are slightly (20%–50%) larger than the infrared sizes of the same galaxies.

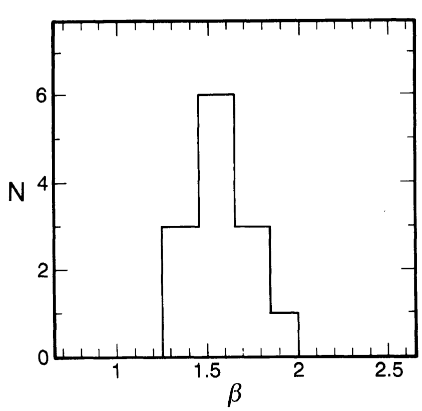

FIG. 3—The distribution of values of β, where $Q(\lambda) \propto \lambda^{-\beta}$, required for a single-temperature fit to the 60 μm, 100 μm, and 1.25 mm flux densities for the galaxies in Table 1.

It is found from these maps that, for the current sample, only three galaxies have radio emission extending beyond a diameter of 30″: NGC 337, NGC 1055, and NGC 7541. Gaussian fits to NGC 1055 and NGC 7541 yield semimajor axes 90″ and 60″ in extent (at full width half-maximum), respectively (Condon et al. 1990). For NGC 337, no Gaussian fit was given, but the radio map indicates an irregularly shaped source with a size at half-maximum of roughly 90″. No attempt has been made to correct for the possible lost emission in these sources. However, for the remaining 14 galaxies, the radio emission is less than 30″ in angular extent. Since the 1.25 mm emission should follow the far-infrared emission, the sources should be smaller at 1.25 mm than at 20 cm (Bicay and Helou 1990). Thus for at least 14 of the 17 galaxies in the current sample, no beam size correction to the 1.25 mm flux densities is required.

The result from this section is that, for the galaxies in this analysis, the long-wavelength absorption efficiency of the dust grains is characterized by $\beta \gtrsim 1$. Since the theory of the long-wavelength absorption efficiency of small grains readily allows for values of β as small as 1 (see, e.g., Bohren and Huffman 1983; Tielens and Allamandola 1987; Wright 1987), it follows that *all of the 1.25-mm measurements in Table 1 are consistent with the hypothesis that these galaxies contain no dust colder than that responsible for the 60 and 100 μm emission.*

3.3 The Upper Limit to the Mass of Cold Dust

Theories of the long-wavelength properties of interstellar dust show that β should lie between 1 and 2 (Bohren and Huffman 1983). One can also use the 1.25 mm measurements, with a dust grain absorption efficiency $\beta = 2$, to obtain an estimate of the mass of cold dust that may be present in these galaxies.[2] For one of the galaxies, NGC 1055, the measured 1.25 mm flux density is low enough, with no aperture corrections necessary, to require $\beta \sim 2$, and hence this galaxy cannot contain cold dust in sufficient quantities to provide any detectable emission unless beam size effects are invoked. However, for the remaining galaxies, the measurements allow room for significant emission at 1.25 mm from cold dust.

Carico (1991) has used the energy distributions from 1 to 1250 μm for 12 of these sources (galaxies *not* included are NGC 337, NGC 1055, NGC 1143/4, UGC 5101, and NGC 6286) to obtain estimates of the distribution of dust

[2]It is true that values of β larger than two are theoretically possible (see Bohren and Huffman 1983); however, most analyses of astrophysical dust grains concentrate on values of β between one and two.

mass as a function of dust temperature for $\beta=2$ and dust temperatures ranging from roughly 10 K up to typically 200 K. For all 12 of the galaxies, cold dust—i.e., dust at temperatures below that obtained from a single-temperature fit to the *IRAS* 60 and 100 μm flux densities—represents more than 90% of the total dust mass obtained by integrating over the entire range of temperatures. Thus, if one adopts a dust grain absorption efficiency with $\beta=2$, in most cases the resulting mass of cold dust is roughly an order of magnitude greater than that inferred from *IRAS* observations alone and dominates the total dust mass in these galaxies. Physically, this means that the cold dust has a sufficiently low emissivity per unit mass that it must dominate the galaxy's mass to produce detectable emission at 1.25 mm.

4. SUMMARY AND CONCLUSIONS

Millimeter observations of 17 high-luminosity infrared-bright galaxies can be fitted by single-temperature energy distributions with dust absorption efficiencies having power law indices $Q(\lambda)\propto\lambda^{-\beta}$ when $\beta\gtrsim 1$. Hence, this analysis does *not* require significant quantities of cold dust in the interstellar medium of these galaxies. This conclusion is in agreement with that of Eales et al. (1989).

Also in agreement with Eales et al. (1989) is the fact that the current 1.25 mm measurements cannot actually rule out the *possibility* of large quantities of cold dust in the majority of these galaxies. In fact, from the results of this analysis, it is possible that the dust mass in some of the galaxies may be dominated by very cold dust. The difficulty in verifying or eliminating this possibility lies in the uncertainty in the long-wavelength absorption efficiency of the dust grains. The mean value of the spectral index of the long-wavelength absorption efficiency obtained using single-temperature curves for the 13 galaxies listed in Table 1 which were detected at 1.25 mm is $\beta=1.6$, which agrees well with the value of 1.65 found recently by Wright et al. (1991) from *COBE* observations of the Galaxy.

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