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MILLIMETER OBSERVATIONS OF A COMPLETE SAMPLE
OF IRAS GALAXIES: DUST EMISSION
AND ABSORPTION IN SPIRALS

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We report on observations performed at 1.25 mm of a southern galaxy sample, selected from the IRAS PSC and complete to $S_{10} = 2 Jy$. We detected 18 sources and set significant limits on 10 further objects. We use these data to discuss the spatial distribution of cold dust, the broad-band far-IR/mm spectra, the overall amount of dust, the gas-to-dust mass ratio, the dust optical depth, and the overall extinction, for such a representative galaxy sample. These results are also supported by a successful comparison with values inferred for the Galaxy. Because of the favourable observational setup, selection wavelength and completeness, we believe these data provide an unbiased view of dust properties in spiral galaxies.
1 Introduction

Observations of diffuse dust in galaxies have a profound impact on our understanding of some basic questions about their structure and past history. IRAS survey data by themselves, unfortunately, do not completely characterize the dust content and emission properties. Dust colder than 20 K, whose existence is currently matter of so much controversial discussions, can only be sampled at $\lambda > 100\mu m$ (Chini et al., 1986).

We report here on a 1.25 mm continuum survey of a complete sample of IRAS galaxies performed with the SEST telescope. The latter was chosen because it provided the best compromise between detector sensitivity and spatial resolution. The 24" FWHM of the SEST beam at 1.25 mm and the average optical extent of the sample galaxies match favourably, so that the beam-aperture corrections needed to compare with the IRAS survey data are not as severe as for other observational setups.

Observations at such long wavelengths ensure that all possible dust components with temperatures down to the fundamental limit, set by the 3 K background radiation, are properly sampled. The use of a complete flux-limited sample ensures a minimal exposure to the effects of bias. Finally, adoption of a far-IR selected sample, rather than of an optical one, makes us confident that the whole phenomenology of dust effects in galaxies is properly explored.

2 Observations and data analysis

The target sample has been selected from the IRAS PSC and is complete to $S_{25\mu m} \geq 2$ Jy. It consists of 29 galaxies with morphological types from S0/a through Scd, within the sky region $21^h < \alpha(1950) < 5^h$ and $-22.5^\circ < \delta < -26.5^\circ$. Distances (mostly from distance indicators, others derived using $H_0 = 75$) cover the range from $d \approx 20$ to $\approx 200$ Mpc. Half-optical-light diameters $A_e$ are typically within $A_e \approx 10^\prime$ to $\approx 40^\prime$, 3 exceptionally close galaxies having $A_e \leq 100^\prime$.

The volume test ($< V/V_{\text{max}} >= 0.45 \pm 0.06$) ensures the sample completeness.

The observations have been done at 230 GHz during September 1990 and 1991 with the MPHFR $^3$He-cooled bolometer (Kreysa 1990) at the SEST 15m telescope. A three-beam modulation is achieved by chopping ON-OFF the source with a beam separation of 70". Pointing accuracy was most of the time close to 2". The overall flux accuracy is estimated to be 10 to 30%.

2.1 Beam-aperture corrections: the size of galaxies at $\lambda = 1.25$ mm

For the 4 optically most extended sources we have performed a rough mapping, which allowed us to reduce the corresponding large aperture corrections. More generally, our adopted procedure was to test various different hypotheses about the distribution of the millimetric emission (see Andreani & Franceschini, 1992): (a) that the mm source is a point-source; (b) that its radial distribution is an exponential with scale-length $a_{mm} = 1/3 \alpha_o$ ($\alpha_o$ is the B-band scale-length); and (c) that the distribution closely follows that of the optical light ($\alpha_{mm} = \alpha_o$).

We show in Figure 1 a plot of the ratios of the 1.25 mm to the 60 and 100 $\mu m$ fluxes versus galaxy distance and diameter, with $S_{1.25}$ corrected according to hypothesis (c). We see that the latter implies rather significant dependences of the average flux ratios, which are not expected (note that all flux measurements have already been K-corrected). We are led to conclude that the hypothesis of a comparable distribution of cold dust and starlight, and even worse that assuming dust present to large radial distances, appear to be inconsistent with our data. Instead, the case for a higher concentration of dust, with $a_{mm} = \alpha_o/3$, is supported by our observations.
2.2 The average galaxy spectrum from 20 to 1300 \( \mu m \)

Figure 2 shows the average far-IR/millimeter spectrum for 28 galaxies in our sample. All fluxes have been color- and K-corrected, taking into account the overall system response, while \( mm \) fluxes have been corrected assuming \( \alpha_{mm} = \alpha_0/3 \). The average 1.25 \( \mu m \) to 100 \( \mu m \) flux ratio turns out to be \( \simeq (3.1 \pm 0.5) \times 10^{-3} \). Beam corrections following hypotheses (a) and (c) above would bring this ratio to values of \( \simeq (2.2 \pm 0.5) \times 10^{-3} \) and \( \simeq (6.2 \pm 0.5) \times 10^{-3} \), respectively.

The main conclusion that can be drawn from Fig. 2 is that there is no evidence in our data of major spectral components of dust emission peaking at \( \lambda > 100 \mu m \), as previously suggested by some authors.

3 The dust model

Our adopted scheme of galactic dust involves a "cirrus" component, including cold dust and small transiently-heated hot grains, and warm dust in starbursting regions (Rowan-Robinson, 1986, 1992, hereafter RR86, RR92; Mazzei et al., 1992).

The "cirrus" component has been modelled following in detail the recipes by RR86 and RR92. The grain mixture (nine grain types in total) and properties have been optimized by RR92 to reproduce all basic observables (e.g. the extinction law) over the entire spectral range from 1 \( \mu m \) to 0.1 \( \mu m \).

For the warm dust in star-forming regions we have followed the approach of Xu and De Zotti (1989) and Conte (1993). The starforming region is modelled as a volume uniformly filled with dust and radiation, and is assumed to be optically thin at least for \( \lambda > 20 \mu m \). The same grain mixture as for the "cirrus" component is adopted, but very small grains are assumed to be destroyed by the intense radiation field.

Three parameters, i.e. the average radiation field intensity \( \chi_c \) in the cold "cirrus", the intensity illuminating the warm dust in starburst regions (\( \chi_w \)) and the light fraction \( f_w \) at 100 \( \mu m \) contributed by warm dust, fully describe the dust model.

The temperatures for all grain types of both dust components are uniquely determined by the parameters \( \chi_c \) and \( \chi_w \), and obtained by solving the usual energy balance equation. The fitting procedure assumes that the 1.25 \( mm \) flux is dominated by cold "cirrus" dust, which basically defines \( \chi_c \). The 60 and 25 \( \mu m \) data mostly define the other two parameters.

4 Results

The adopted dust model turns out to be particularly successful in reproducing the observed far-IR/mm broad-band spectra for all the sample galaxies.

The dashed line in Fig. 2 corresponds to the "cirrus" component fitted to the average galaxy spectrum, the dot-dashed to the average starburst component. We report in Table 1 various details on the physical parameters (temperature, mass) of the dust components for this best-fit model. Note in particular that the warm "starburst" component is found to contribute only a few \% of the total dust mass.

For thirteen galaxies, that we name "cirrus"-dominated, the contribution of warm dust appears to be negligible. Fifteen objects require, instead, high values of the warm dust fraction \( f_w \geq 0.4 \), and their spectrum at \( \lambda < 100 \mu m \) is dominated by warm dust in the starburst component (the starburst-dominated galaxies).

An overall view of dust effects in our IR galaxies is given in Figure 3. The observed optical depth \( \tau_B \) has been estimated from the total dust mass divided by the projected area within one third of the optical radius, where we estimate dust is confined. \( \tau_B \), which measures the amount of dust available to absorb optical light, is compared in Fig. 3 with a quantity \( A_B \) measur-
ing the overall actual effect of extinction. \( A_B \) has been estimated from the logarithmic ratio of the bolometric optical-UV luminosity \( (L_O) \) to the bolometric far-IR light \( (L_{FIR}) \). The two galaxy classes that we have defined appear significantly segregated over this plane, the inactive "cirrus"-dominated objects being confined to low values of dust optical depth \( (\tau_B \leq 1) \) and low extinction \( (A_B \geq 0.5) \).

The active star-forming galaxies, on the contrary, are spread over much larger values in both axes: appreciable amounts of dust and extinction seem to characterize only these objects, with typical \( \tau_B \) of 1 to 10. However, only for a minority of these objects \((5/16)\), extinction values significantly higher than 1 are indicated.

Finally, we report in Figure 4 a plot of the gas to dust ratio versus bolometric luminosity \( (L_{d+g} = L_O + L_{FIR}) \). Gas masses (including both HI and molecular gas estimated from CO observations) are from Andreani et al. (1994). The median \( L_{d+g} \sim 5 \times 10^{10} \) for the inactive objects is a factor 2 lower than the corresponding value of starbursts, consistent with our inference that the latter are characterized by an enhanced SFR. Second, the median gas/dust ratio for the two classes also differs \((< M_g/M_d > \sim 300 \) for the starbursts and \( \geq 1000 \) for the inactive population). Finally, there is an apparent trend of \(< M_g/M_d > \) to decrease with \( L_{d+g} \) for the inactive galaxy population.

The positions that our Galaxy would occupy in both Fig. 3 and 4 have been determined by applying our adopted dust model to the galactic integrated spectral emissivity. Its position, well within the region occupied by the inactive population in Fig. 3, is consistent with our finding that the Galaxy’s far-IR spectrum is dominated by "cirrus" emission.

5 Discussion

A fruitful combination of good sensitivity at long wavelengths, a fairly large beam aperture and small angular size of the target objects, have allowed us to explore the dust content in galaxies down to the coldest possible temperatures and over most of the optical galaxy extent. Although our inferences on the mm size of galaxies have only a statistical sense, our results (Fig. 1) appear inconsistent with the assumptions that cold dust has a scale-length comparable to or larger than that of starlight. They rather suggest that the mm scale-length is 1/3 or so of the optical one. This may reflect the observed increase in metallicity towards the inner regions of galaxies (e.g. Sodrowski et al., 1994) and may be consistent with the idea of an enhanced past stellar activity there.

The observed millimetric emissivity of these galaxies seems also inconsistent with large spectral components appearing longward of 100 \( \mu \)m. The bolometric corrections to the far-IR IRAS data needed to estimate the global dust emissivity appear to be rather small.

A published model (RR92) reproduces very accurately the observed broad-band spectra. A simple color criterion, supported by model predictions, exploiting the millimetric fluxes and IRAS data, allows to classify these IR galaxies according to the rate of star-formation.

Model inferences on the dust mass imply B-band optical depths within one third of the optical radius spanning a large range of values \((\tau_B = 0.1 \) to 10, see Fig. 3). The largest values of dust mass, optical depth and the dust/gas mass ratio are shared by objects characterized by a starbursting activity \((\tau_B > 1)\). The inactive "cirrus"-dominated galaxies, which are the typical population that bright optical samples select, seem almost unaffected by dust. These results are confirmed by a comparison with the actual \( A_B \) extinction inferred from the observed ratio of optical to far-IR bolometric emissions. Relatively high values of \( A_B \) \((> 1)\) are displayed only by a minority of the starbursting galaxies \((5 \) over \( 29 \) objects of the total sample). Note, however, that the large values of \( A_B \) in these objects are
likely to reflect more the IR emission from starbursting regions than extinction really affecting the whole galaxy body.

Our data efficiently constrain the presence of cold dust in galaxies. In our model, dust at $T \approx 7$ to $\approx 20K$ is responsible for most of the millimetric emission (see Table 1). The corresponding dust mass evaluation then accounts also for very cold dust components in the ISM, whose mass fraction however appears to be modest. To get a stronger constraint, we have also considered the possible existence of a dust component illuminated by a very dim radiation field ($\chi = 0.5 \chi_\odot$), with a temperature distribution ranging from 4 to 18 K. Our data imply that no more than $10^7 M_\odot$ of such cold dust may exist in our average galaxy: this, added to the other two components, would only bring to a 40% increase of the overall estimated dust mass with respect to our previously discussed best-fit. Altogether, dust of any kind does not seem to play a major role in extinguishing the stellar emission.

There are some intriguing effects to notice in Fig. 4. The starbursting activity seems to imply a heavier dust enrichment of the ISM with respect to inactive spirals: $M_d/M_s$ values are typically $\approx 1000$ for the latter, while ranging from 100 to 1000 for starbursts. The ongoing starburst may well have reprocessed the ISM in these objects significantly longer or more efficiently than inactive galaxies did.

Finally, there seems to be a trend favouring higher values of $M_d/M_s$ in lower luminosity normal inactive spirals. This may parallel a similar trend of higher metallicities at higher masses inferred for early-type galaxies.

A comparison with results obtained for the Galaxy seems to support our conclusions. Its observed spectral emissivity strongly supports our adopted dust model. Its inferred overall extinction and dust column density are as expected (Fig. 3). The somewhat low value of $M_d/M_s$ observed in Fig. 4 with respect to those of non-starbursting galaxies of the same luminosity may simply reflect the fact that the galactic value refers to the inner dusty regions, whereas those of galaxies in our sample include also the contributions of gas in the outer dust-poor environments.

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REFERENCES
Kreysa E., 1990, in From Ground-Based to Space-Born Sub-mm Astronomy, ESA SP-314, p.265-270
Mazzu, P., Xu, C., and De Zotti, G., 1992, A&A 256, 45
Rowan-Robinson, M., 1986: MNRAS 219, 737 (RR86)
Rowan-Robinson, M., 1992: MNRAS 258, 787 (RR92)
Figure 1: Millimetric to far-IR flux ratios versus galaxy distance (left-hand panels) and apparent diameter (right-hand). The millimeter fluxes $S_{1.25}$ have been corrected for beam-aperture assuming a mm scale-length equal to that of the optical light. The two lines in each panel correspond to the ±1 $\sigma$ regression fits obtained with a "survival analysis" technique. The corresponding values of the correlation coefficient are also reported.

Figure 2: Average far-IR/mm broad-band spectrum for our sample galaxies, with the corresponding "cirrus" (dashed line) and starburst (dot-dash) contributions. The corresponding best-fit spectral parameters are $\chi_r = 11$ (normalized the intensity in the solar neighbourhood), $\chi_u = 120$ and $f_u = 0.3$. The continuous line is the summed contribution. Values of the physical parameters for this dust model are detailed in Table 1.

Figure 3: Observed optical depth of dust $\tau_B$ versus the overall extinction $A_B$. $\tau_B$ is averaged within one third of the B-band Holmberg radius (the deprojected face-on $\tau_B$ scales from this value with the galaxy axial ratio $b/a$ squared). $A_B$ is estimated by comparing the bolometric outputs in the optical and far-IR. Open and filled squares refer the the inactive "cirrus"-dominated and to the starbursting objects. The solar symbol marks values estimated for the Galaxy, by applying our dust model to its global spectral emissivity. The predicted dependences for a screen, a slab, and a sandwich (with zero scale-height of dust) model are shown for comparison (Disney et al., 1989).

Figure 4: The gas to dust mass ratio versus bolometric optical/mm luminosity (symbols as in Fig. 3). The dotted line is an eye-fit to the locii of the "cirrus" galaxies.