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LETTER

Letter to the Editor

ISOPHOT boosts dust masses in spiral galaxies*

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Abstract. We report photometry with ISO between 60 and 200μm of six galaxies. Three of them are active and the extension of their spectra beyond the IRAS bands up to 200μm confirms our previous conception that most of the dust there is warm and has a fairly uniform temperature of $\sim$30 K. In the other three galaxies which are inactive, we detect a very cold component ($\sim$10 K and less) that could hitherto at best be surmised. The most dramatic consequence is a threefold increase in the mass of interstellar material over what one would calculate without the ISO data.

Key words: galaxies: interstellar matter – galaxies: dust

1. Introduction

The gas content $M_{\rm gas}$ is one of the fundamental parameters of a galaxy because it provides the reservoir for star formation. Probably the best method to estimate it is by observing around 1 mm the optically thin emission of dust. The detected flux S_λ and the total dust mass $M_{\rm d}$ are directly proportional: $M_{\rm d} = S_\lambda / D^2 K_\lambda B_\lambda(T_{\rm d})$. Here K_λ is the absorption coefficient per gram of dust at wavelength λ, $B_\lambda(T_{\rm d})$ denotes the Planck function at temperature $T_{\rm d}$ and D is the distance to the galaxy. To translate the dust mass $M_{\rm d}$ into gas mass $M_{\rm gas}$ one needs a conversion factor R; the value for the Milky Way, which is about 150, may serve as a guiding number.

In this Letter, we are only concerned with $T_{\rm d}$, not with the dust–to–gas ratio R nor with K_λ. The dust temperature derives its significance mainly from two facts. First, it appears in the above equation for the dust mass. Second, because dust emission is proportional to $T_{\rm d}^6$, moderate digressions in temperature are associated with large changes in energy. If new far IR photometry forces us to revise the temperature of the cold dust in a particular galaxy, say from T_2 to a smaller value T_1, the gas mass goes up from its previous estimate, whatever it was, by a factor $B_\lambda(T_2)/B_\lambda(T_1)$, because the new photometry will leave R, D and K_λ unchanged. If we do not touch K_λ, the proposed drop in temperature has the further consequence that the average heating rate in the galaxy must be a factor $(T_1/T_2)^6$ smaller than hitherto thought. The latter implies that the cold dust is either better shielded, or farther away from the stars, or the average stellar luminosity per unit volume is lower.

2. Observations

We used ISOPHOT (Lemke et al. 1996) on board the satellite ISO (Kessler et al. 1996) for far IR photometry of six galaxies (see Table 1). NGC 6156, NGC 6918 and NGC 7083 are spirals without any clear sign of activity and with an optical diameter D_{25} of 90", 60" and 240", respectively. The Markarian galaxies Mkn 534, Mkn 538 and Mkn 928 are supposed to be active and have optical sizes of $\sim$120". We observed in the OFF–ON mode with the standard multi-filter template PHT22 (Klaas et al. 1994) in 8 filters of the C100 and C200 detector. Exposure times were 32s per position. The OFF–positions are clean on the IRAS 100μm plates and typically 10 arcmin away from the source. Data reduction was done with PIA[1]. It corrects for non–linearities of the integration ramps, glitches, responsivity drifts (Laureijs et al. 1996) and includes background subtraction and color corrections (Klaas 1997) assuming a spectral shape $\nu^2 B_\nu(T_{\rm d})$.

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[1] PIA is a joint development by the ESA Astrophysics Division and the ISOPHOT Consortium led by the MPIA, Heidelberg. Contributing ISOPHOT Consortium institutes are DIAS, RAL, AIP, MPIK, and MPIA.

Table 1. FIR fluxes from ISOPHOT in Jy. Fluxes at 1.3mm with two 3σ–upper limits are from SEST and MRT and in mJy.

Object	S_{60}	S_{80}	S_{90}	S_{105}	S_{120}	S_{150}	S_{180}	S_{200}	S_{1300}
NGC 6156	16.9 ± 2.9	33.0 ± 5.2	31.4 ± 4.8	41.6 ± 6.2	29.2 ± 3.6	28.2 ± 3.6	18.1 ± 2.4	15.2 ± 2.2	255 ± 77
NGC 6918	9.3 ± 1.7	16.1 ± 2.8	14.1 ± 2.4	15.4 ± 2.4	10.4 ± 1.3	8.9 ± 1.2	6.1 ± 0.8	5.6 ± 0.8	112 ± 33
NGC 7083	6.6 ± 1.0	15.6 ± 2.2	19.8 ± 2.6	29.2 ± 3.9	26.0 ± 3.1	30.0 ± 3.5	20.2 ± 2.4	20.4 ± 2.5	119 ± 36
Mkn 534	7.5 ± 1.8	13.8 ± 2.7	11.6 ± 2.2	13.5 ± 2.2	8.9 ± 1.2	8.9 ± 1.2	6.7 ± 0.9	6.3 ± 1.0	< 7.2
Mkn 538	13.5 ± 2.7	17.9 ± 3.2	14.6 ± 2.7	13.3 ± 2.1	8.5 ± 1.2	8.0 ± 1.1	5.3 ± 0.8	5.5 ± 0.8	< 11.1
Mkn 928	10.4 ± 2.4	16.7 ± 3.2	13.6 ± 2.6	13.0 ± 2.2	8.8 ± 1.2	8.8 ± 1.2	6.4 ± 0.8	6.1 ± 0.8	6.7 ± 2.1

To derive the temperature of the coldest dust component, we complement the ISO photometry with 1.3 mm fluxes. The awkward task is to spatially match them with the C200 ISO data as the latter refer to a beam of 138" to 184". For the inactive spirals, we use the 1.3 mm maps by Chini et al. (1995). They have a linear size of 72", but are undersampled. We account for the incomplete coverage by forming the mean flux per unit solid angle at the observed positions and distribute it evenly over a circle of 72" diameter. For NGC 6156 and NGC 6918, it is assumed that the 1.3 mm emission does not extend beyond this circle as their optical diameter D_{25} is comparable with the map size. For NGC 7083 the optical image is greater and therefore we additionally increase its 1.3 mm flux by 30%. In all galaxies the 1.3 mm continuum is contaminated by the CO (2–1) line. In NGC 6156 and NGC 7083, the contamination in the 24" central beam amounts to $\sim$20% (Chini et al. 1995; Chini & Krügel 1998) and is expected to be less in the outer parts of the galaxies. We account for the line contribution by reducing all above derived 1.3 mm fluxes by 10%. Note that if we apply no corrections at all to the 1.3 mm fluxes, the temperature of the cold component in NGC 6156 and NGC 6918 goes up just 2 K compared to what we will derive (see below).

For the Markarian galaxies we have much less information on their size at FIR/mm wavelengths. The 1.3 mm fluxes refer to a 12" area in the center (Chini & Krügel 1998). Because of their weakness, no maps have been obtained so far at 1.3 mm. However, there are CO data at various apertures for Mkn 538 (Chini & Krügel 1998). They suggest that this object is quite compact, not more than than 24" in diameter, but bigger than 12". A size between 12" and 24" seems to be a general feature of Markarians according to previous CO observations (Chini et al. 1992). We estimate the corrections to the 1.3 mm flux due to a somewhat larger extent of the galaxies to be $\sim$50%. On the other hand, the average line contamination at 1.3 mm for the Markarian galaxies is above 20%, i.e. stronger than in inactive spirals (Chini & Krügel 1998). In view of our limited knowledge about the source size, we take the observed 1.3 mm continuum data from a 12" beam at their face value and combine them with the ISOPHOT data.

3. Results

Naturally, the IR spectrum of a galaxy originates from grains at all possible temperatures; if they are tiny their emission is even time–varying. The temperatures we are talking about are derived from photometry and are therefore color temperatures; they represent the physical grain temperature only when one uses the correct slope $dK_\lambda/d\lambda$. To simplify matters, we approximate the observed fluxes between 60 and 1300μm by just two components of spectral shape $\nu^2 B_\nu(T_\mathrm{d})$. To this end, we perform least–square fits weighting all points by their statistical error. At 1.3 mm we have increased all errors to 33% in view of the uncertainties in line contamination and emitting area.

Table 2. Coordinates, distances in Mpc based on H_0 = 75 km s^{-1} Mpc^{-1} and IR luminosities in $L_\odot$ from 12 to 1300μm for the observed galaxies.

Object	1950 coordinates		D	L_{IR}
NGC 6156	16 30 28.2	-60 30 55	43.5	2.0 10^{11}
NGC 6918	20 27 15.4	-47 38 33	24.0	2.8 10^{10}
NGC 7083	21 31 50.0	-64 07 33	41.1	7.9 10^{10}
Mkn 534	23 26 13.8	03 14 14	68.4	3.8 10^{11}
Mkn 538	23 33 39.9	01 52 35	37.6	1.7 10^{11}
Mkn 928	23 15 47.5	-04 41 21	98.3	7.1 10^{10}

The best fit for NGC 6156 and NGC 6918 yields two distinct components. One is extremely cold with a temperature $T_c \simeq 9$ K which in terms of galactic molecular clouds is as low as one can find it. The other has $\sim$30 K which corresponds to an average over a star forming complex in the Milky Way. In NGC 7083, the temperatures are less disparate, T_c is not extreme, but still lower than most previous estimates for galaxies. The statistical error ΔT in the temperature determinations is $\sim$4 K and we consider $T_c + \Delta T$ as an upper limit to the temperature of the *bulk* of dust. Cooler dust, and plenty of it, may of course exist. Only the temperature of the cold component, T_c, is relevant for the mass determination, the mass associated with the warm component ($\sim$30 K) is some 30 times less. T_c had generally been thought to be about 20 K in inactive spirals (see for instance the numerous references in Sect. 4.4 of Reach et al. 1995). When we repeat the fits without ISOPHOT data, we get in all three galaxies for the cold component a temperature around 18 K. The two times lower temperatures when ISOPHOT data are included, at least for NGC 6156 and NGC 6918, imply about three times more interstellar mass.

To derive actual numbers for the dust masses, we assume a mixture of silicate and amorphous carbon grains with a mass ratio $m_\mathrm{Si}/m_\mathrm{C}$ = 1.5. With the optical constants of Laor & Draine (1993) and Zubko et al. (1996) (type BE), respectively, one finds

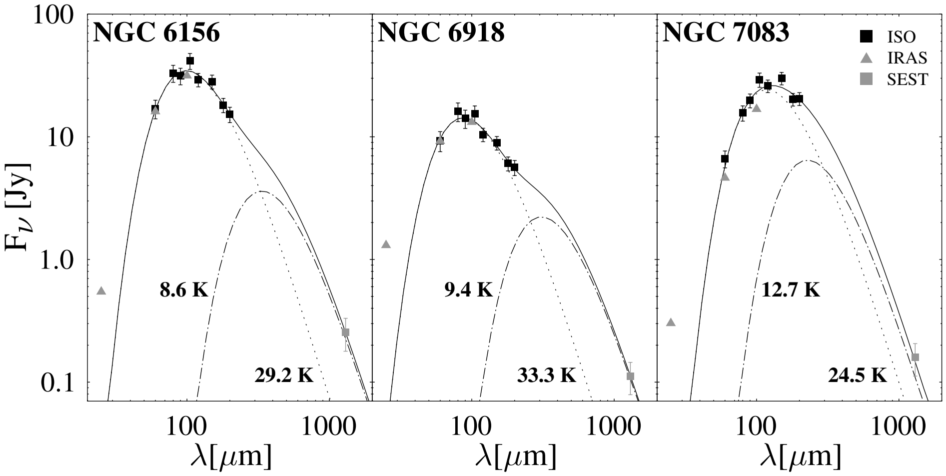

Fig. 1. Dust emission spectra of three inactive spiral galaxies. The dotted and dash–dotted lines are two–component least–square fits between 60 and 1300μm of the form $\nu^2 B_\nu(T_{\rm d})$, the solid curves give their sum. Fit temperatures are indicated.

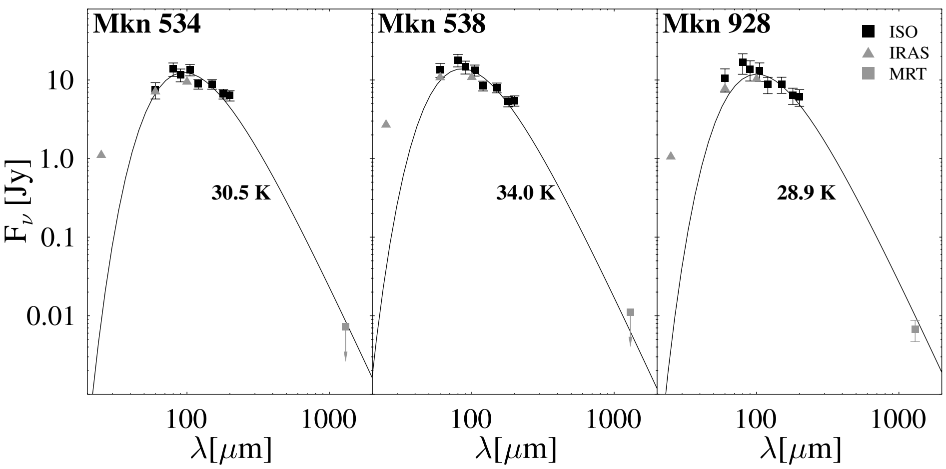

Fig. 2. Dust emission spectra of three active galaxies from the Markarian catalog. The solid lines are one–component fits between 60 and 1300μm of the form $\nu^2 B_\nu(T_{\rm d})$. Fit temperatures are indicated

absorption efficiencies $Q_{1.3{\rm mm}}({\rm Si}) = 0.86a$ and $Q_{1.3{\rm mm}}({\rm C}) = 2.13a$ and an absorption coefficient $K_{1.3{\rm mm}} = 0.37\,{\rm cm}^2$ per gram of dust, independent of grain radius a. Using the temperatures as shown in Fig. 1, this results in total dust masses of $9.0\,10^8\,{\rm M}_\odot$ for NGC 6156, $1.0\,10^8\,{\rm M}_\odot$ for NGC 6918 and $2.0\,10^8\,{\rm M}_\odot$ for NGC 7083. They are a factor of 3.1, 2.6, 1.6, respectively, higher than those derived with a dust temperature of 18 K, as was indicated before ISO.

Very cold dust had already been hypothesized from IRAS fluxes (Devereux & Young 1990). Less speculative, as there were submm/mm data, but still on shaky grounds because of missing 200μm points, was the suggestion that in the galaxy UGC 3490 most of the dust may have only 9 K (see Fig. 6a in Chini et al. 1995). This possibility is supported by the present ISO photometry. The Milky Way would be interesting for comparison, but it seems not easy to determine what its spectrum would look like *from outside*. One component of $\sim$20 K was claimed to account for almost all emission between 100 and 1300μm in its inner part (see Fig. 2 of Cox & Mezger (1989) for a compilation of data). More recent COBE/FIRAS observations (Wright et al. 1991, Reach et al. 1995) do not really contradict this finding, but show additional evidence for dust of 4 . . . 7 K. However, in the spectral decomposition the emission of this extremely cold dust is not dominant at 1 mm, whereas our 10 K components make up for most of the 1 mm fluxes.

For the three Markarian galaxies the ISOPHOT data do not lead to any qualitatively new conclusions, but corroborate old ones (Chini et al. 1989). All spectra are roughly similar and may be approximated by a single component indicating that the dust is uniformly warm. The temperature average over the three sources is $\sim$31 K. There is no pressing need for a second component, although it would of course improve the quality of the fits. The errors ΔT of the one–component fits are around 3 K. When we tentatively take into account that the objects are probably larger than 12" and increase the 1.3 mm fluxes by 50%, the average temperature decreases to $\sim$28 K.

4. Conclusions

We have observed with ISOPHOT three quiescent and three Markarian galaxies, now fully covering the maximum of infrared emission. In combination with our 1.3 mm fluxes, we find that most dust in the inactive galaxies is very cold, 10 K or even less. As corresponding estimates without ISOPHOT data ranged around 20 K, the new temperature values imply a considerable increase in the dust mass, possibly a factor of three. As the three galaxies are typical members of our sample of inactive galaxies (Chini et al. 1996), we expect that in a large fraction of inactive spirals most of the dust is very cold, 10 K or less, and that and there is more interstellar matter than we thought. Active galaxies are characterized by warm dust of a uniform temperature of about 30 K with no indication for cold grains; this is probably the result of the strong concentration of both dust and luminosity in the centers of active galaxies. Before ISO, resolving the far IR spectra into temperature components was very problematic because of the large observational gap between 100 to 1300μm for most objects, with ISO the situation has much improved.

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