DUST MASSES, PAH ABUNDANCES, AND STARLIGHT INTENSITIES IN THE SINGS GALAXY SAMPLE

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1. PURPOSE

Fundamental Task

Determination of the physical properties of interstellar dust grains in the galaxies

Why? Dust is important to understand physical phenomenon with a major role in ***the process of star formation***.

How? Fit ***Physical dust models*** to the SINGS galaxy samples with infrared (IR), far-infrared (FIR), and submillimeter photometry.

→ They estimate various dust properties and search the relationship between dust properties and other physical properties for these galaxies.

2. INTRODUCTION(1)

●Interstellar Dust

•Interstellar dust absorbs short-wavelength (ultraviolet) radiation radiated from stars and ionized gas, and reradiate infrared (IR), far-infrared (FIR), submillimeter, millimeter, and microwave emission.

•We are able to investigate the chemical and physical information in the star-forming regions and the interstellar medium (ISM) of galaxies by observing dust emission in long-wavelength.

●SINGS galaxy samples

•The SINGS(***SI**RTF* **N**earby **G**alaxy **S**urvey) is a comprehensive infrared imaging and spectroscopic survey of 75 nearby galaxies.

•These samples are observed with all instruments on the Spitzer Space Telescope.

•Theses samples are also supplemented with extensive observational data at other wavelengths.

2. INTRODUCTION(2)

●"PAH index" q_{PAH}

PAH index q_{PAH}, defined to be the percentage of the total grain mass contributed by PAHs containing less than 10^3 C atoms, characterize the PAH abundance.

$$q_{\mathrm{PAH}} \equiv \frac{M(\text{PAHs with } N_{\mathrm{C}} < 10^3)}{M_{\mathrm{dust}}} \qquad (1)$$

●Dust-to-Gas mass ratio

IF
1) The interstellar abundances of all heavier elements were proportional to the gas-phase oxygen abundance,
2) The same fraction of the major condensable elements (C, O, Mg, Si, Fe) were in solid form as in the Milky Way (MW).

All galaxies will be expected to confirm to the following formula.

This value of M_{dust}/M_H is the priori expectation.

$$\frac{M_{\mathrm{dust}}}{M_{\mathrm{H}}} \approx 0.010 \frac{(\mathrm{O/H})}{(\mathrm{O/H})_{\mathrm{MW}}} \qquad (2)$$

3. DATA

●IRAC(3.6, 4.5, 5.7, 7.9 μ m) and MIPS(24, 71, 160 μ m)

•In 75 SINGS galaxy samples, they excluded 10 galaxies because of foreground/ background contamination, saturation, and so on. Thus, the sample they studied here consists of 65 galaxies.

●IRS 16 μ m

•IRS 16 μ m photometry are available for 11 of the SINGS galaxies that they studied this paper.

●SCUBA(450, 850 μ m)

•SCUBA observations at 450 and/or 850 μ m are available for 17 of 65 SINGS galaxy samples they studied this paper.

•For 17 galaxies, the dust models are constrained by 850 μ m SCUBA data in addition to IARC and MIPS data (they refer to these as the SINGS-SCUBA galaxies).

●IRAS(12, 60, 100 μ m) and ISO(6.75, 15 μ m)

•Because IRAS photometry is obtained from SCANPI data for most SINGS galaxy samples, They use IRAS photometry in their model fitting.

•ISOCAM photometry are shown in this paper, but these data are not used in model fitting.

4. DUST MODELS(1)

●Physical dust mixture

•They employed the dust models that consist of specified mixtures of **carbonaceous grains** and **amorphous silicate grains**, including the fraction of **PAH index** q_{PAH}, ranging from q_{PAH} **= 0.4%** to q_{PAH} **= 4.6%** in steps of **0.1%**.

•The dust size distributions are chosen to reproduce the observed wavelength-dependent extinction in the local MW.

•They assumed the simplification as follow,

1. They do not include **silicate absorption at 9.8 μ m** in their dust models.
2. They do not include **H_2O** and other **ices** in their dust models.

TABLE 3
PHYSICAL DUST MODELS

j_M	Model	q_{PAH} (%)	M_{dust}/M_H [a,b]	A_V/N_H (mag cm^2 H^{-1})
1	MW3.1_00	0.47	0.0100	5.3×10^{-22}
2	MW3.1_10	1.12	0.0100	5.3×10^{-22}
3	MW3.1_20	1.77	0.0101	5.3×10^{-22}
4	MW3.1_30	2.50	0.0102	5.3×10^{-22}
5	MW3.1_40	3.19	0.0102	5.3×10^{-22}
6	MW3.1_50	3.90	0.0103	5.3×10^{-22}
7	MW3.1_60	4.58	0.0104	5.3×10^{-22}
8	LMC2_00	0.75	0.00343	1.2×10^{-22}
9	LMC2_05	1.51	0.00344	1.2×10^{-22}
10	LMC2_10	2.40	0.00359	1.2×10^{-22}
11	SMCbar	0.010	0.00206	6.2×10^{-23}

[a] $M_H \equiv M(\text{H I} + H_2)$.
[b] $M_{dust}/M_{gas} = [M_{dust}/M_H]/1.36$.

4. DUST MODELS(2)

●Starlight intensity models

They specify the intensity of the radiation that is heating the dust grains.

✓Simplification

•They adopt the spectrum of the local interstellar radiation field (ISRF) as the average spectrum of the interstellar radiation in a normal spiral galaxy.

•A large fraction of the dust in a galaxy is located in the diffuse ISM where the dust is heated by a single radiation field, with **intensity factor** $\boldsymbol{U = U_{min}}$.

•A small fraction of the dust in a galaxy is located in regions where the radiation field is more intense, with a wide range of intensity factor from $\boldsymbol{U = U_{min}}$ to $\boldsymbol{U = U_{max} >> U_{min}}$.

$$\frac{dM_{\rm dust}}{dU} = (1-\gamma)M_{\rm dust}\delta(U - U_{\rm min}) + \gamma M_{\rm dust}\frac{(\alpha - 1)}{U_{\rm min}^{1-\alpha} - U_{\rm max}^{1-\alpha}}U^{-\alpha}$$

γ : the fraction of dust mass in regions with $U > U_{min}$

4. DUST MODELS(3)

● **The model emission spectrum**

$$F_{\nu,\mathrm{model}} = \underbrace{\Omega_\star B_\nu(T_\star)}_{①} + \frac{M_{\mathrm{dust}}}{4\pi D^2}\left[\underbrace{(1-\gamma)p_\nu^{(0)}(j_M, U_{\mathrm{min}})}_{②} + \underbrace{\gamma p_\nu(j_M, U_{\mathrm{min}}, U_{\mathrm{max}}, \alpha)}_{③}\right], \quad (3)$$

$$\chi^2 \equiv \sum_b \frac{\left(F_{\mathrm{obs},b} - \langle F_{\nu,\mathrm{model}}\rangle_b\right)^2}{\sigma^2_{\mathrm{obs},b} + \sigma^2_{\mathrm{model},b}}, \quad (4)$$

① The stellar contribution by a blackbody with color temperature $T_* = 5000\mathrm{K}$.

② The dust contribution that is heated by a general diffuse ISRF with uniform intensity $U \sim U_{min}$.

③ The dust contribution that is heated by the high-intensity regions with $U > U_{min}$, including PDRs.

✓ ***Parameters***

$$\boldsymbol{M_{dust}},\ \boldsymbol{q_{PAH}},\ \boldsymbol{U_{min}},\ \boldsymbol{U_{max}}\ (=10^6),\ \boldsymbol{\gamma},\ \alpha\ (=2),\ \Omega_*$$

5. RESULTS (SINGS-SCUBA GALAXIES)

● **Dust Models Fitting**

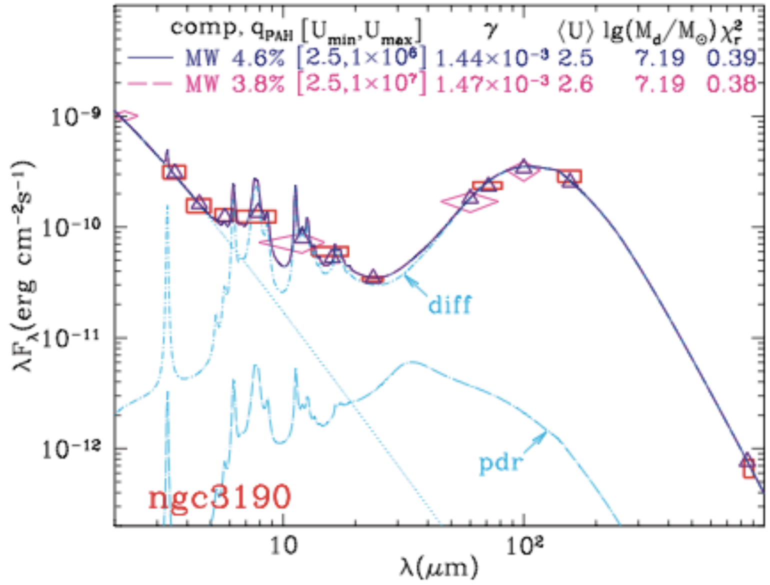


Fig. 3a

Fig. 1(a)

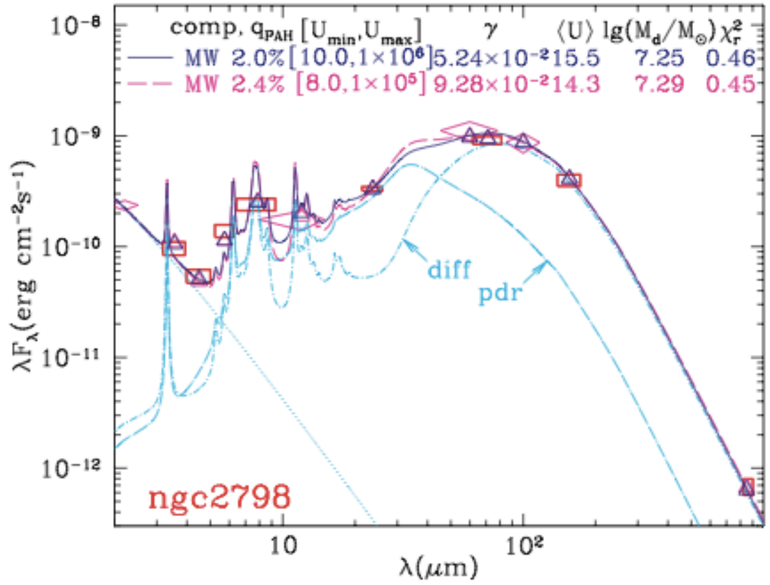


Fig. 3b

Fig. 1(b)

•They fit the models to the subset of 17 SINGS-SCUBA galaxies, and estimate their model's fitting parameter (M_{dust}, q_{PAH}, γ , U_{min}, and mean starlight intensity $<U>$).

The models are generally very successful in fitting the observed SEDs !!

5. RESULTS (SINGS-SCUBA GALAXIES)

●Radiation Field Parameters : U_{min}

•Figure 2 show the distribution of the best-fit **minimum starlight intensity scale factor U_{min}** obtained for 17 SINGS-SCUBA galaxies.

There are no cases that the best-fit models have $U_{min} < 1$, even though the model-fitting procedure considered the selected values of U with $0.1 < U < 10^7$.

They concluded that cool dust grains in dark clouds (grains inside dark clouds, shielded from external starlight, will have $U << 1$) make a very small contribution to the overall FIR emission.

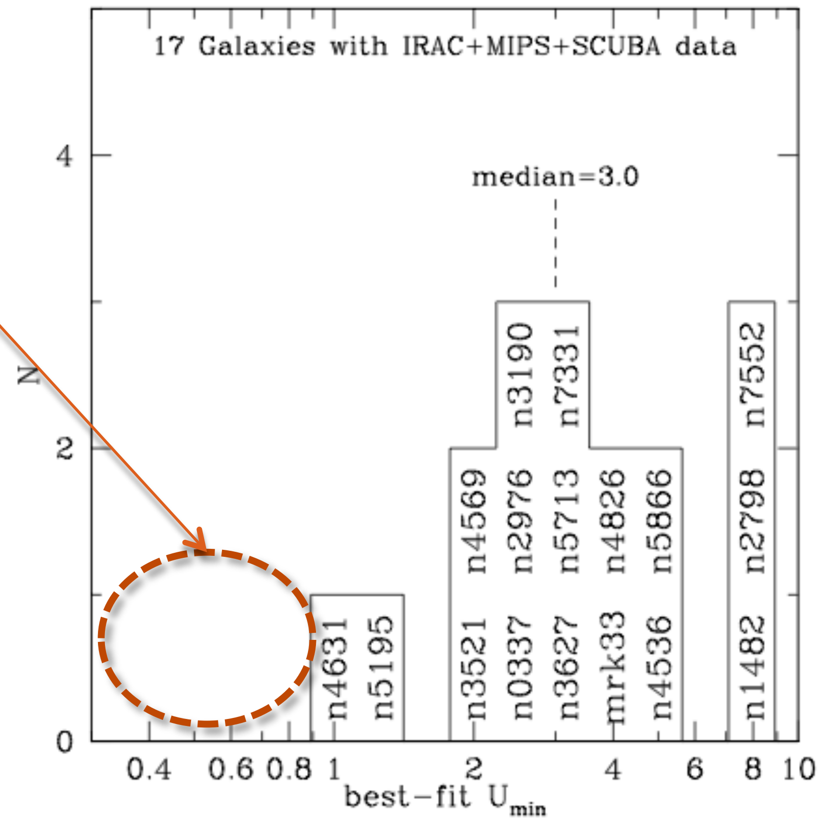


Fig. 2

5. RESULTS (SINGS-SCUBA GALAXIES)

●Radiation Field Parameters : <*U*>

•The **dust-weighted mean starlight intensity scale factor <*U*>** is

$$\langle U\rangle = \left[(1-\gamma)U_{\rm min} + \frac{\gamma \ln(U_{\rm max}/U_{\rm min})}{U_{\rm min}^{-1} - U_{\rm max}^{-1}}\right] \quad (5)$$

•Figure 3 show the distribution of <*U*> obtained for 17 SINGS-SCUBA galaxies.

•<*U*> ranges from 2.2 to 16, with a median of 4.32.

•As seen figure, these galaxies tend to have <*U*> ≥ 2.

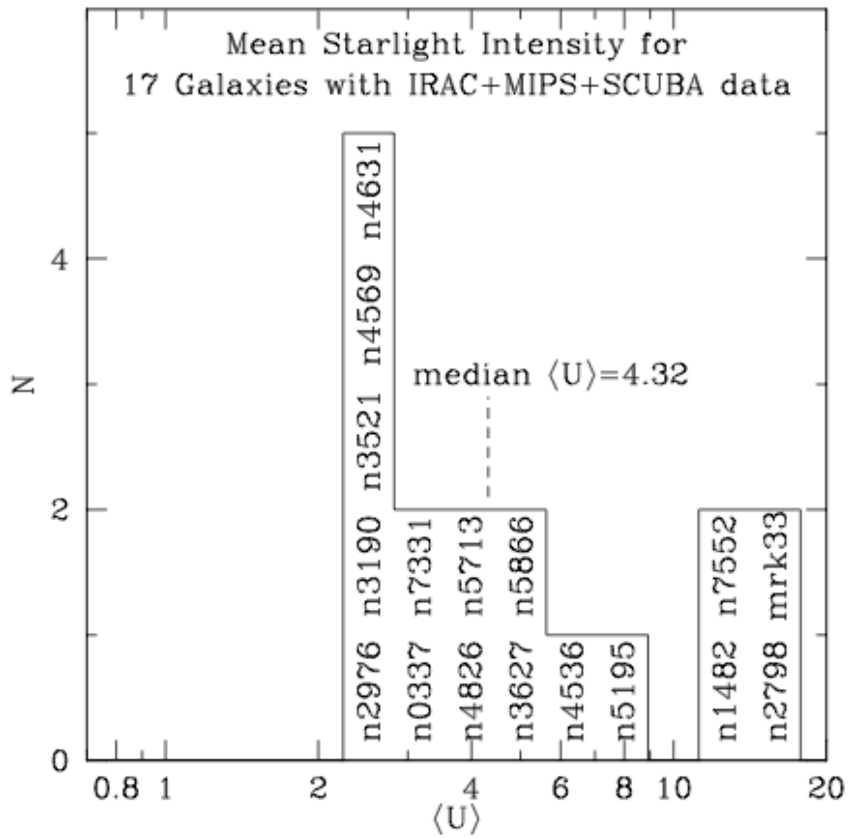


Fig. 3

5. RESULTS (SINGS-SCUBA GALAXIES)

●Dust-to-Gas Mass Ratio

•Because 21 cm emission and CO emission are measured for 12 SINGS-SCUBA galaxies, they estimate the masses of H_I and H_2 for these galaxies.

•Figure 4 shows dust-to-hydrogen gas mass ratio for 12 SINGS-SCUBA galaxies for which the total (atomic and molecular) gas masses are known.

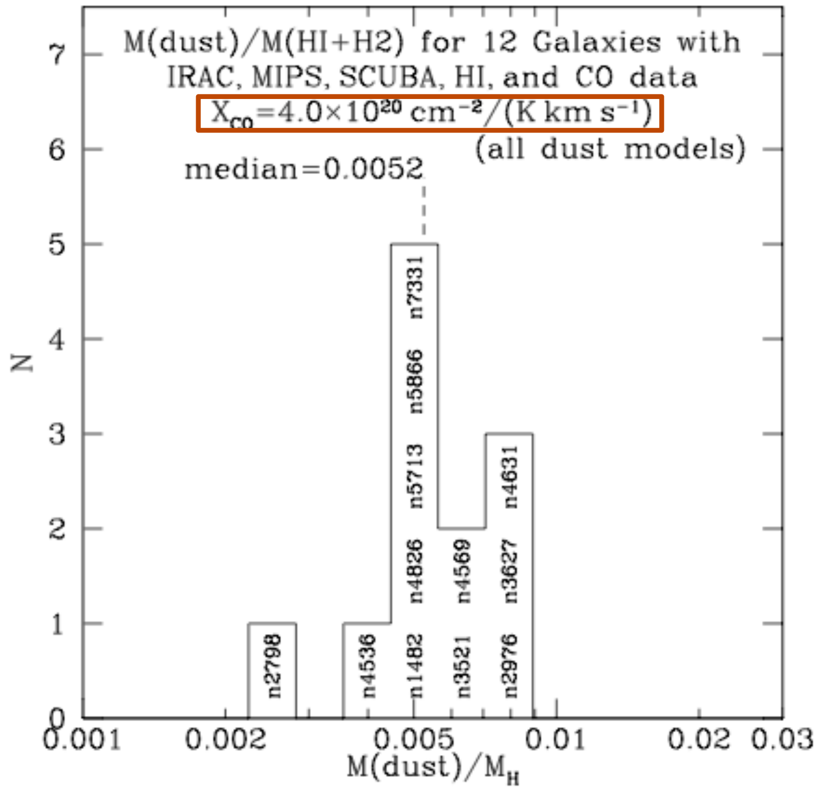


Fig. 4

The derived dust-to-gas ratios have median $M_{dust}/M_H \approx$ **0.0052**.

Roughly Similar !

Ref. •The estimation from depletions in the local MW : ≈ **0.0073**

•The estimation from the models for the observed MW extinction : ≈ **0.010**

6."RESTRICTED" FITTING PROCEDURE

- **The models fitting *without the SCUBA data***

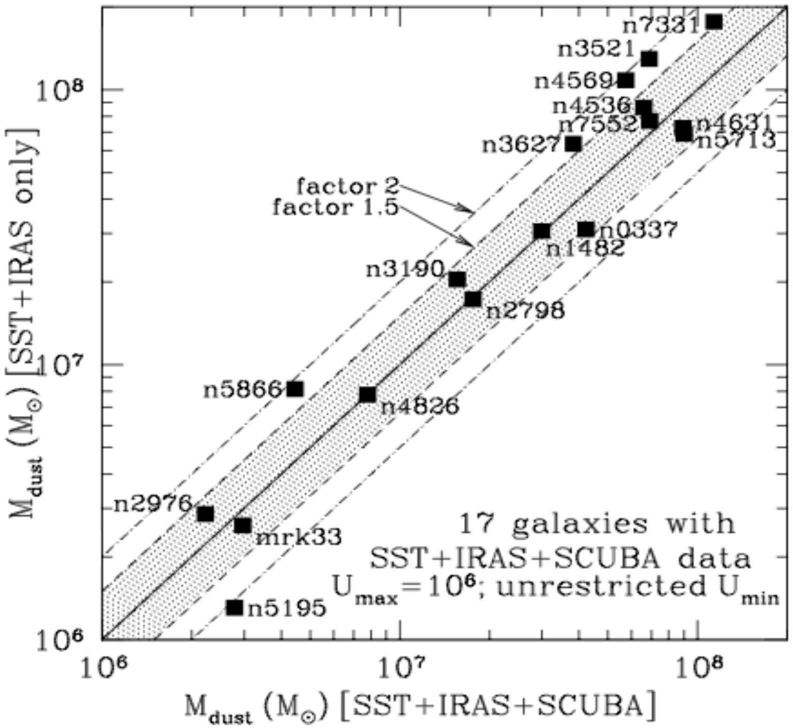


Fig. 5

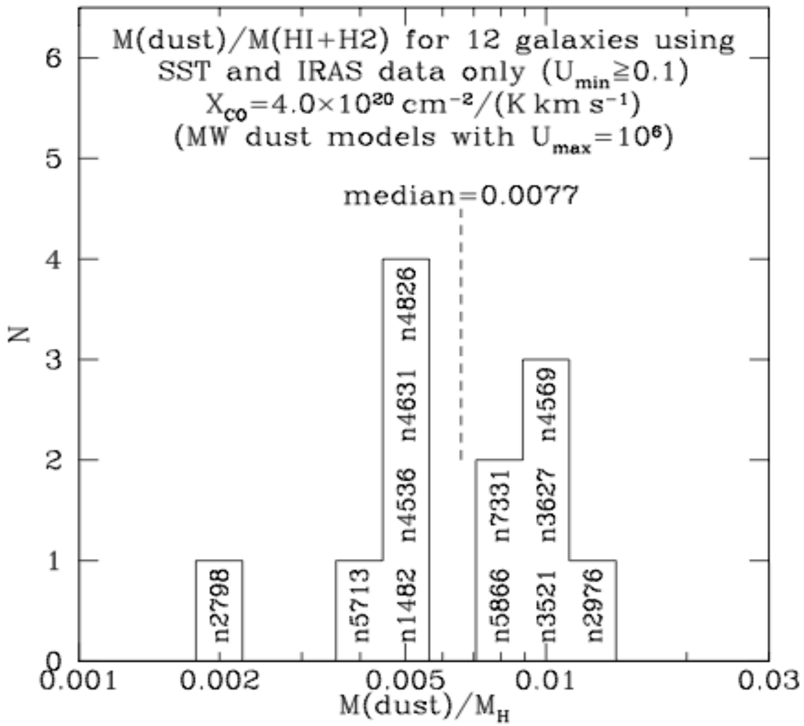


Fig. 6

Fig. 5: The estimated dust masses with **IRAC+MIPS+IRAS** data only,
VS. The estimated dust masses with **IRAC+MIPS+IRAS+SCUBA** data.

Fig. 6: Histogram of dust-to-gas mass ratio estimated without using SCUBA data.

Even in absence of SCUBA data, the dust masses are relatively estimated well.

6. “RESTRICTED” FITTING PROCEDURE

●“restricted” fitting procedure

•When submillimeter data are unavailable, the mass of cool dust in a galaxy is not strongly constrained. Given this situation, there is a risk that the previous model-fitting procedure invoke a large mass of cool dust heated by weak starlight.

•Therefore, they applied the following **“restricted” fitting procedure** to the remaining 48 SINGS galaxies for which submillimeter fluxes are unavailable.

1. Models limited to MW dust models only, with $0.4 \leq q_{PAH} \leq 4.6\%$.
2. $U_{max} = 10^6$.
3. $\alpha = 2$.
4. $0.7 \leq U_{min}$.

They avoid the risk by restricting the value of U_{min}.

7. RESULTS(65 SINGS GALAXIES)

●Dust-to-Gas Mass Ratio

•For 48 SINGS galaxies with only Spitzer and IRAS data, they estimate the dust properties (M_{dust}, U_{min}, $<U>$, q_{PAH}) using the ***"restricted" models-fitting procedure***.

•For 20/48 galaxies, they can estimate the total (atomic and molecular) gas mass because both H_I 21 cm and CO 2.6mm fluxes have been detected.

•For another 24 galaxies, they estimate only a lower limit on the gas mass because either H_I 21 cm or CO 2.6mm flux is unknown.

•Figure 7 shows that same as Fig. 6, but for 20 galaxies lacking SCUBA data.

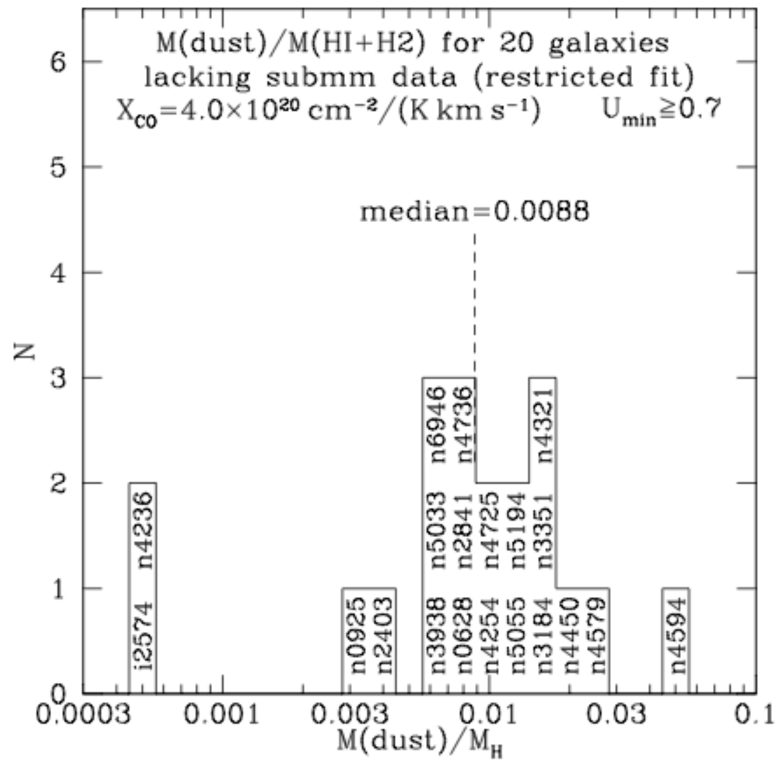


Fig. 7

The distribution of dust-to-gas mass ratio for these galaxies have the median $M_{dust}/M_H \approx 0.0088$, and looks similar to the distribution in Fig. 6.

7. RESULTS(65 SINGS GALAXIES)

●Dust-to-Gas Mass Ratio, VS. Metallicity

•Figure 8 shows the dust-to-gas mass ratio vs. metallicity for 60 SINGS galaxies that consist of not only 32 galaxies for which H_I 21cm and CO 1-0 fluxes have bean measured, but also 28 galaxies for either H_I or CO is unknown.

✧For galaxies with $A_O > \mathbf{8.1}$, upper limits on the global M_{dust}/M_H are generally consistent with equation (2), to within a factor of ~ 2.

In the ISM of these galaxies, grains contain a substantial fraction of interstellar Mg, Si, and Fe as in the case in MW.

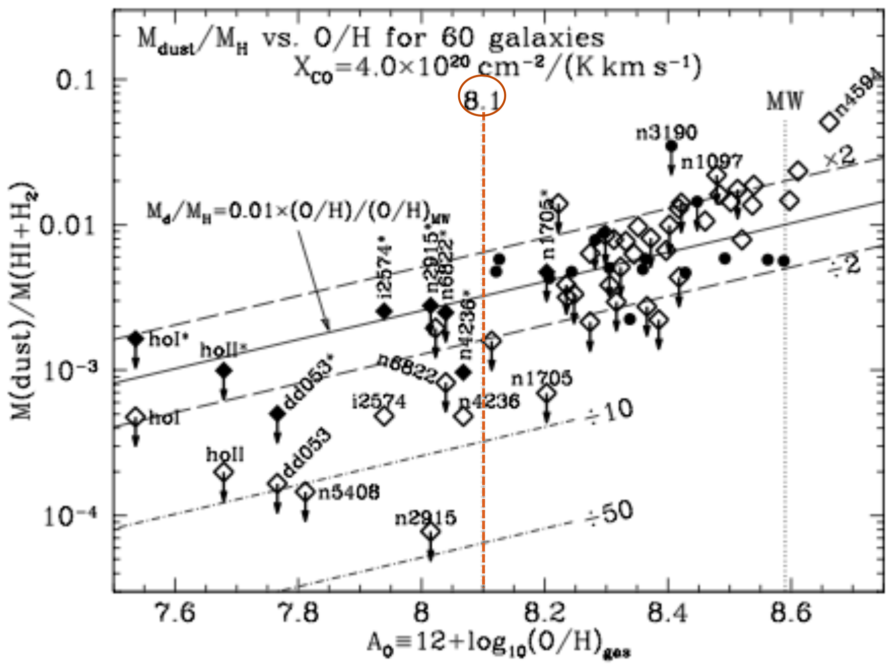


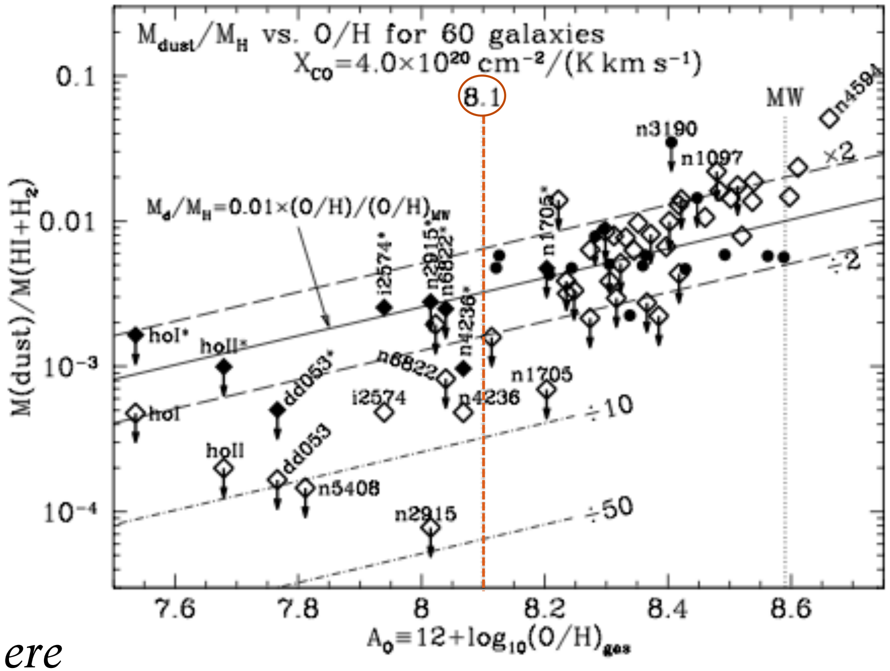
Fig. 8

7. RESULTS(65 SINGS GALAXIES)

✧On the other hand, every galaxy with A_O **< 8.1** has a global M_{dust}/M_H that falls below equation (2).

Why?

- These low-metallicity galaxies are dwarf irregular galaxies.
- In each of these galaxies, most of H I is located outside the region where IR emission is detected.



They estimate M_{dust}/M_H *for the regions where IR emission is detected* (Filled diamonds).

These galaxies have upper limits consistent *with equation* (2) to within a factor of ~ 2.5.

7. RESULTS(65 SINGS GALAXIES)

●PAH Abundance

•Figure 9 shows the distribution of PAH index q_{PAH} for 61 SINGS galaxies except for four galaxies for which the dust emission is so weak that they cannot estimate q_{PAH} reliably.

•In the Figure, shaded histogram show the 17 SINGS-SCUBA galaxies.

The q_{PAH} for these galaxies range from 0.4% to 4.6%, and the distribution is broad.

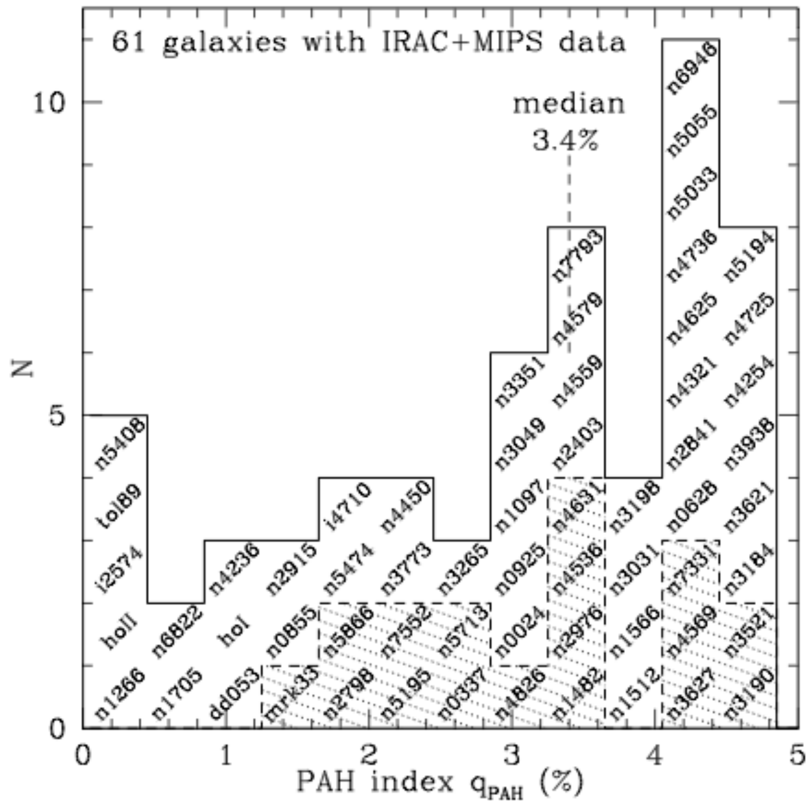


Fig. 9

7. RESULTS(65 SINGS GALAXIES)

●PAH Abundance vs. Metallicity

•Figure 10 shows PAH index q_{PAH} vs. galaxy metallicity (oxygen abundance) for 61 galaxies.

✓The separation is clearly seen in merallicity $A_O = \mathbf{8.1}$.

✧9 galaxies with $A_O < \mathbf{8.1}$ have PAH index $q_{PAH} < 1.9\%$, with the median $q_{PAH} = 1.0\%$.

✧52 galaxies with $A_O > \mathbf{8.1}$ tend to have higher q_{PAH} , with the median $q_{PAH} = 3.55\%$.

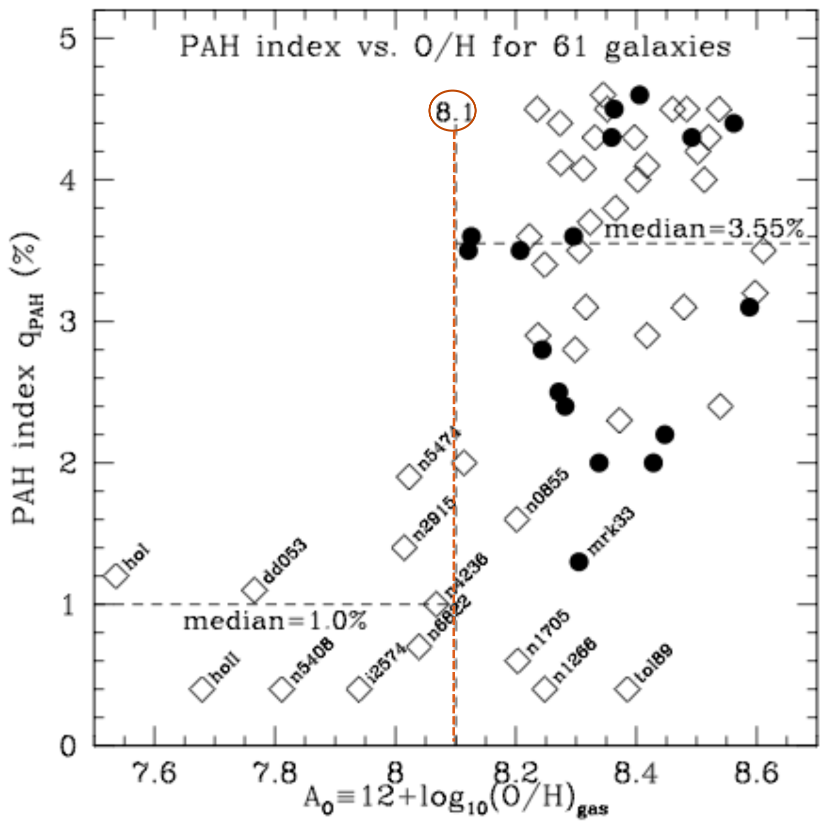


Fig. 9

The PAH abundance is correlated to metallicity.

7. RESULTS(65 SINGS GALAXIES)

●Starlight Properties : U_{min}, $<U>$

Fig. 10 (a) and (b) show the distribution of U_{min} and $<U>$ for 65 SINGS galaxies.

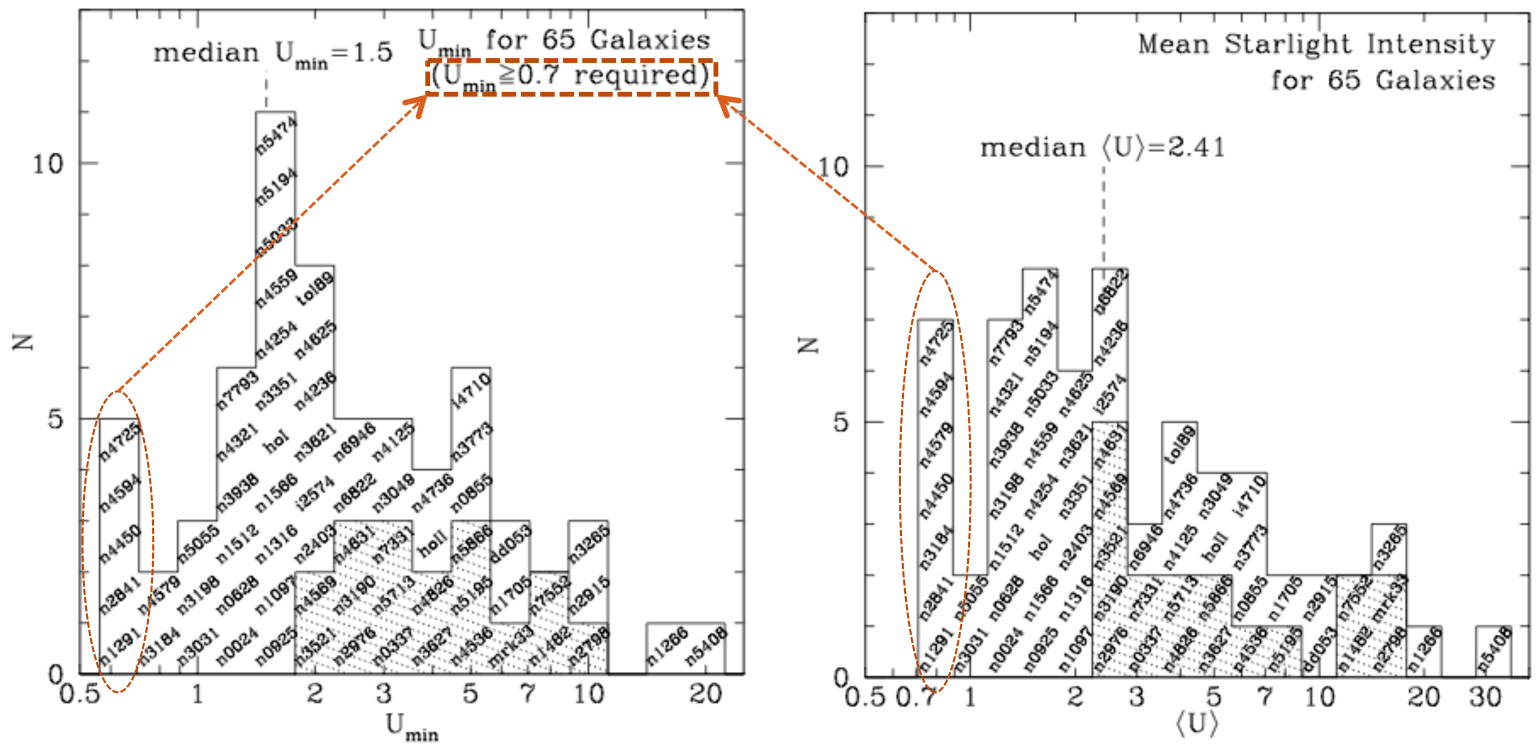


Fig. 10 (a) Fig. 10 (b)

•In Fig. 10 (b), the SINGS galaxy samples show a tendency to have $<U> \approx 2.5$.

•In Fig. 10 (a), the median $U_{min} = 1.5$ is only slightly intense than our local ISRF ($U = 1$) that they adopt when constraining starlight intensity.

7. RESULTS(65 SINGS GALAXIES)

●Contribution of high-intensity regions to the dust heating

•The fraction of the dust luminosity radiated from regions with $U > U_c$ is defined according to the following formula.

$$f(L_{\text{dust}};\, U > U_c) = \frac{\gamma \ln(U_{\max}/U_c)}{(1-\gamma)(1 - U_{\min}/U_{\max}) + \gamma \ln(U_{\max}/U_{\min})}$$

They estimate values of $f(L_{dust};\, U > U_{min})$, $f(L_{dust};\, U > 10^2)$, and $f(L_{dust};\, U > 10^3)$ to investigate the contribution of the dust luminosity radiated from high-intensity regions to the total IR power for 65 SINGS galaxies.

7. RESULTS(65 SINGS GALAXIES)

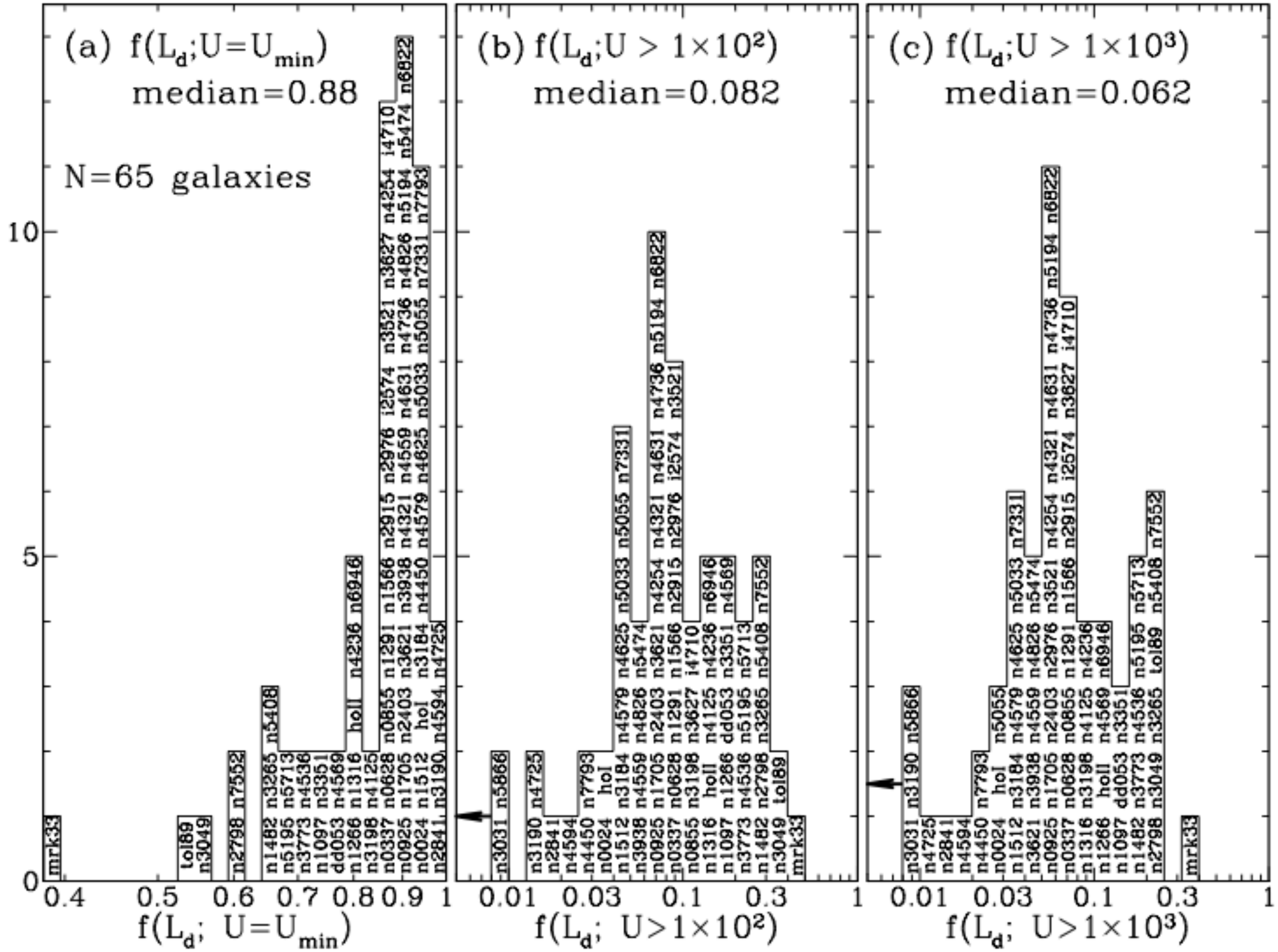


Fig. 11 (a) Fig. 11 (b) Fig. 11 (c)

7. RESULTS(65 SINGS GALAXIES)

●Contribution of high-intensity regions to the dust heating

✓In Fig. 11,

1. Half of 65 SINGS galaxies have $f(L_{dust}; U > U_{min}) \geq 0.8$.
   - **The IR emission for these galaxies are dominated by dust grains in the diffuse ISM.**
2. For 65 SINGS galaxies, the median of $f(L_{dust}; U > 10^2)$ and $f(L_{dust}; U > 10^3)$ are 0.082 and 0.062, respectively.
   - In most of these galaxies, the high-intensity regions are probably PDRs near massive stars.
   - **For the star-forming galaxies, a significant fraction of the dust luminosity from warm dust in the regions of intense starlight is found in the SEDs.**
3. There are the galaxies with the high values of $f(L_{dust}; U > 10^3)$ (e.g. Mrk 33, NGC 3049, Tol 89, and so on).
   - These galaxies appear to be forming stars at a high rate per unit area.

8. SUMMARY

- A physical dust model consisting of PAHs, carbonaceous grains, and amorphous silicate grains heated by starlight, with a distribution of starlight intensity, reproduces the IR and submillimeter emission for SINGS galaxy samples.
- For 17 SINGS-SCUBA galaxies, cold dust grains in dark clouds appear to account for a very small fraction of the overall FIR emission.
- Even when submillimeter data are unavailable, the dust properties are recovered to within a factor of 2.2, with the "restricted" fitting procedure.

8. SUMMARY

- The dust-to-gas mass ratio is correlated with metallicity. The galaxies with $A_O > 8.1$ appear to have global dust-to-gas mass ratios consistent with equation (2), while the galaxies with $A_O < 8.1$ appear to have global dust-to-gas mass ratios that fall below equation (2).

- The PAH index q_{PAH} that characterize the PAH abundance is correlated with metallicity. Metallicity $A_O = 8.1$ appears to mark a transition in the composition of interstellar dust in galaxies, from low PAH to high PAH.

- Half of SINGS galaxies have more than 88% of the total infrared emission provided by dust grains in diffuse ISM. The SEDs for the star-forming galaxies are contributed from a significant fraction of the dust luminosity radiated by warm dust in regions of intense starlight (e.g. PDRs near massive stars).