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Spectral Energy Distributions of Dusty Galaxies

By

Toshinobu TAKAGI,[*] Vladas VANSEVIČIUS,[†] and Nobuo ARIMOTO[‡]

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Abstract: We present a model of spectral energy distributions (SEDs). This model employs two processes of dust heating: heating by radiation and heating by hot gas. The radiation fields and the resulting SEDs are calculated by a software code that treats the radiative transfer by assuming spherical symmetry. Using a dust model with a mixture of graphite, silicate and PAHs, we reproduce the standard extinction curve and the spectrum of the cirrus emission in the Galaxy. The temperature fluctuation of dust particles is taken into account wherever the enthalpy of a dust particle that corresponds to the equilibrium temperature in a given radiation field is less than the energy of one UV photon.
We derived the SEDs of a starburst galaxy (M82), an elliptical galaxy (NGC2768) and a cluster of galaxies (the Coma cluster). The derived age of M82 is 500 Myr when the V-band optical depth, τ_V, is 3.5. In the optically thin case, such as NGC2768, the spatial distribution of dust in the galaxy is derived from the SED fitting, by fixing the size of galaxy. We conclude that the spatial distribution of dust is the same as that of stars in NGC2768. The 120 μm emission from the Coma cluster detected by ISO is reproduced by the model with $\tau_V = 0.002$. It is found that dust particles in the intracluster space is mainly heated by the hot X-ray emitting gas, although the heating by the intracluster radiation field is important for the spectrum at the submillimeter and longer wavelengths.

1. INTRODUCTION

It is well known that the dust particles play an important role in many astrophysical situations. For example, one has to unveil the star formation hidden by dust, in order to understand the formation process of galaxies (Guiderdoni et al. 1997). It is also possible that the reddened starburst galaxies are recognized as extremely red objects, along with elliptical galaxies (Dey et al. 1999). Moreover, a recent observation by ISO shows that the dust also exists in the intracluster space (Stickel et al. 1998). In this work, we produce the spectral energy distributions (SEDs) of starburst galaxies and elliptical galaxies from UV to submillimeter (SMM), and the SED of dust emission of clusters of galaxies heated by the hot intracluster gas and the radiation field.

[*] Department of Physics, Rikkyo University, Japan; takagi@itp.rikkyo.ac.jp
[†] Institute of Physics, Goštauto, Vilnius, Lithuania.
[‡] Institute of Astronomy, School of Science, University of Tokyo, Japan.

2. MODEL DESCRIPTION

2.1 Radiative Transfer

Assuming spherical symmetry, we can solve the radiative transfer, and then calculate the attenuated SEDs of the stellar emission and the dust thermal emission. Isotropic scattering is considered up to six times so that the numerical error due to neglecting higher scattering terms does not exceed 0.3 %. The temperature fluctuation of dust (see below) is simultaneously calculated at each radius for each size of dust grains. The self-absorption by dust is fully taken into account. Although the total numerical error increases as the galaxy becomes optically thick, it is always less than 3 % in the present model.

2.2 Dust Model

The extinction curve observed in the Galaxy has three prominent features. The very small graphite is a candidate for the carrier of the feature at 2175 Å, while the rest of features at 9.7 and 18 μm is commonly attributed to the resonances of silicate grains (Draine & Lee 1984). We adopt the graphite-silicate model developed by Draine & Lee (1984), and add new species of dust particles that cause narrow emission features in the near- and mid-infrared regions. These emission features are attributed to the vibrational transitions of C-H and C-C bonds on the polycyclic aromatic hydrocarbons (PAHs; Leger & Puget 1984). The optical properties of PAHs are taken from Desert, Boulanger, & Puget (1990). The size distributions of graphite and of silicate grains are assumed to be power laws with the exponent, $\beta = -3.5$ for the size range from 0.01 μm to 0.25 μm (e.g. Mathis, Rumpl, & Nordsiek 1977). In order to change the amount of very small graphite independent of that of big grains, a different exponent, γ, is adopted in place of β for graphite grains smaller than 100 Å. The size of PAHs is assumed to the average value, corresponding to 90 carbon atoms in a PAH molecule (Leger, d'Hendecourt, & Defourneau 1989).

For a given radiation field, the equilibrium temperature of a dust grain can be evaluated under the assumption that the energy absorbed per unit time is the same as that emitted. When the enthalpy of a particle corresponding to the equilibrium temperature is less than the energy of one UV photon, the particle cannot attain the temperature equilibrium, but the temperature will fluctuate. We follow the method outlined by Guhathakurta & Draine (1989) to calculate the temperature distribution function of the dust particle. The calculated distribution functions of graphite grains irradiated by the interstellar radiation field in the solar neighbourhood are shown in figure 1. When the size a = 200 Å, the distribution function is so narrow that its temperature can be represented by its equilibrium value, while a dust grain smaller than 100 Å tends to be transiently heated by a UV photon.

The extinction curve and the diffuse emission spectrum from dust in the Galaxy are presented in figures 2 and 3, respectively. The adopted relative mass fractions of graphite, silicate, and PAHs are 0.45, 0.5 and 0.05, respectively. This amount of the very small graphite corresponding to γ = -3.75 is required to explain the observed intensity at 25 μm. Throughout this paper, we use this dust model for the Galaxy.

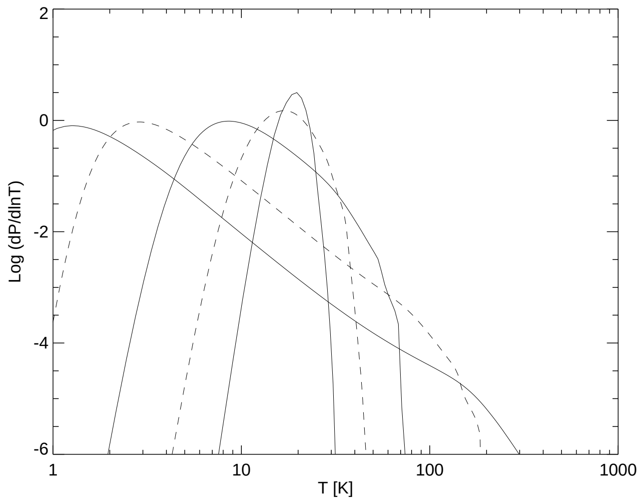

Fig. 1: The temperature fluctuation of graphite grains with size of 10, 20, 50, 100, 200 Å in the solar neighbourhood radiation strength (solid and dashed lines). The size increases from the broader curve to the narrower.

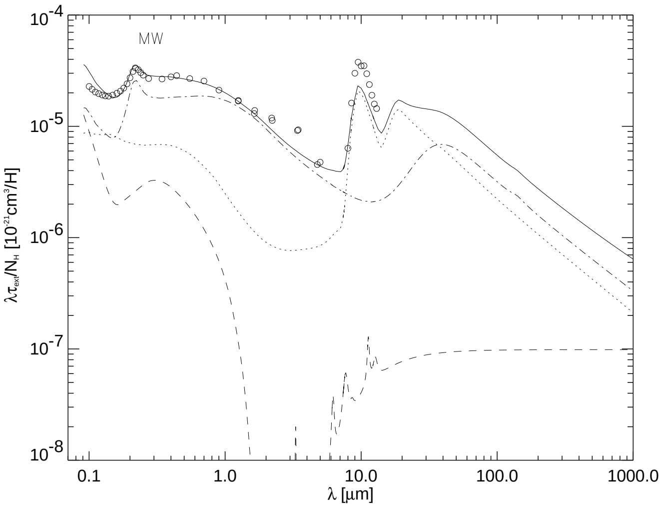

Fig. 2: The extinction curve in the Galaxy. The solid curve is for the total extinction, the dot-dashed curve for graphite grains, the dotted curve for silicate grains and the dashed curve for PAHs. The open circles are the average value of extinction taken from Pei (1992) for UV-NIR and Rieke & Lebofsky (1985) for $\lambda > 5.0\mu$m.

3. SEDS OF GALAXIES

3.1 M82

We assume an instantaneous burst of star formation to reproduce the SED of the starburst galaxy, M82. The simple stellar population model by Kodama & Arimoto (1997) was adopted. The distribution function of stars is assumed according to the King model (King 1962), while

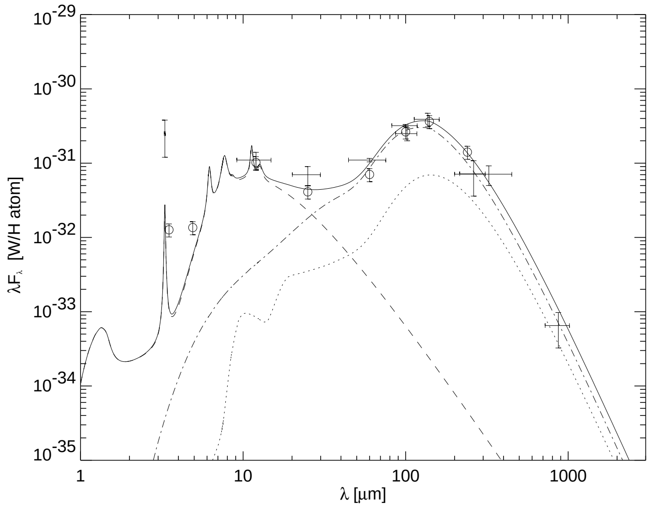

Fig. 3: SED of the cirrus emission. Line symbols are the same as in figure 2. The data points are taken from Desert, Boulanger, & Puget (1990), and Dwek et al. (1997)

the dust particle is homogeneously distributed. The best fit is achieved with the age, t, of 500 Myr and the optical depth at V band, τ_V, of 3.5. The result is shown in figure 4. By using the derived mass and age of the starburst, the average star formation rate is found to be 30 $M_\odot \mathrm{yr}^{-1}$. The SED of M82 shows colour red enough to be recognized as an extremely red galaxy at redshift > 1. We see that the model underestimates the flux around 25μm. This may suggest a limitation of the present model, in which the interstellar matter is assumed to be one component, instead of multicomponents as observed.

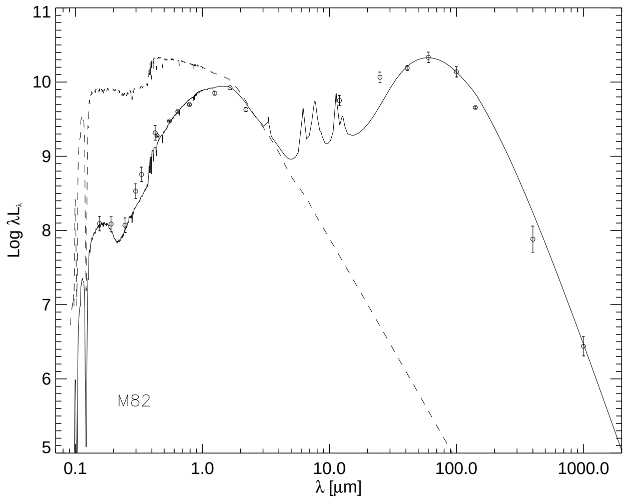

Fig. 4: The SED of M82. The solid line is for age, $t = 500$ Myr and $\tau_V = 3.5$. The dashed curve indicates the intrinsic stellar SED.

3.2 NGC2768 - an Elliptical Galaxy

NGC2768 is one of very few elliptical galaxies detected in the SMM waveband. We adopt the galactic wind model to reproduce the stellar SED (Kodama & Arimoto 1997). Since the reddening by dust is negligible in this case, only the SED of the dust emission can restrict the spatial distribution of the dust and τ_V. The results of fitting to this object are shown in figure 5. While the amount of dust is determined from the luminosity of dust emission, both the spatial distribution of dust and the galaxy size affect the peak wavelength of dust emission. Once the galaxy size is determined observationally, one can derive how dust particles distribute in an elliptical galaxy from the emission peak. For NGC2768, we conclude that the spatial distribution of dust is the same as that of stars. The luminosity of dust emission is reproduced by $\tau_V = 0.3$, which corresponds to $8.0 \times 10^5 M_\odot$ of dust mass in this galaxy.

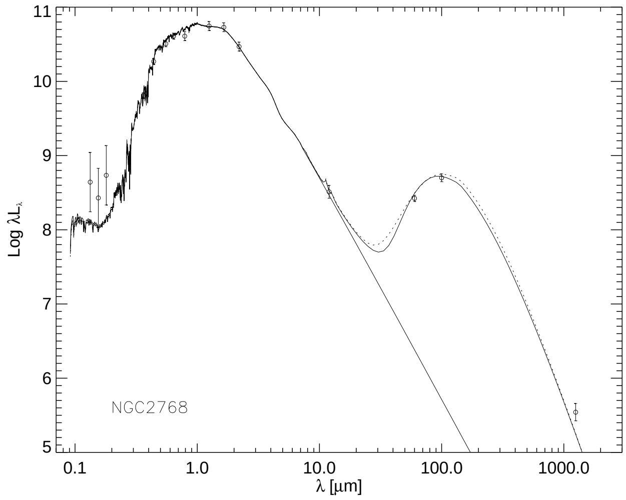

Fig. 5: SED of an elliptical galaxy, NGC2768. The upper solid curve at the FIR is for the model with $\tau_V = 0.3$, in which the same distribution is adopted for stars and dust. The dotted curve indicates the model with homogeneous distribution of dust. The former model gives consistent galaxy size with the observation.

4. DIFFUSE FIR EMISSION OF COMA CLUSTER

The existence of dust in the intracluster space has been deduced from extinction measurements. Zwicky (1962) estimated the extinction of light from distant clusters by nearby ones for the first time. For the Coma cluster he found $A_V = 0.4$, while Boyle, Fong, & Shanks (1988) found a value of $A_V = 0.15$ for the average cluster extinction. More recently, Stickel et al. (1998) reported the first detection of such intracluster dust emission by using ISO.

In the intracluster space, the main source of dust heating is the hot gas emitting X-ray rather than the ambient photon radiation field (see figure 7), although the heating by the radiation field is important in the SMM region and beyond. It is difficult for dust grains to reach their equilibrium temperature, because the mean time interval between heating events is too long for the typical number density of hot gas, $\sim 10^{-3}$. The distribution of dust is assumed to be King-like and the same as that of hot gas derived from the surface brightness of X-ray.

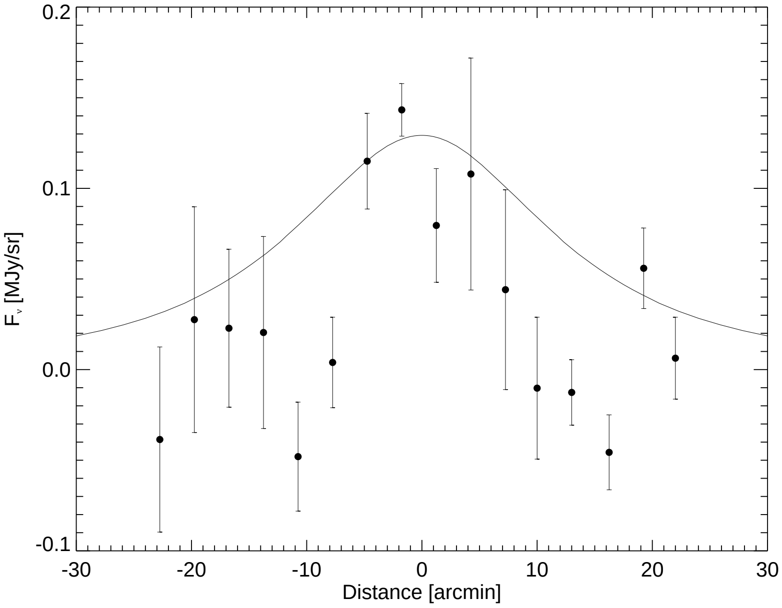

Fig. 6: The surface brightness profile of the Coma cluster at 120 μm. The data are taken from Stickel et al. (1998). The King profile is adopted for the distributions of galaxies and dust. The core radius of dust is 1.6 times greater than that of galaxies. The solid curve indicates the model with $\tau_V = 0.002$.

The radial distribution of galaxies are also assumed to be the King profile. The adopted core radii are 0.25 Mpc and 0.4 Mpc for galaxies and dust, respectively. In figure 6, we show the surface brightness profile of dust emission observed by ISO. The resulting $\tau_V = 0.002$ is two order of magnitude less than the value derived from the extinction observation as pointed out by Dwek et al. (1990). If both measurements are real, the cold dust that cannot be detected at 120 μm by ISO must exist. In figure 7, we show the SED of intracluster dust. The dotted curve shows the sum of the SEDs of elliptical galaxies in the cluster. Thus, the observed FIR emission clearly exceeds the superposition of point source. Without hot gas, the dust becomes too cool for emission to be detected.

5. SUMMARY

We present the model SEDs in which the two heating processes of dust can be considered; the photon radiation and the hot gas. The SED of prototypical starburst galaxy, M82 can be reproduced with the age of 500 Myr and τ_V of 3.5. In the optically thin case like elliptical galaxies, the spatial distribution of dust is restricted by the SED fitting with the galaxy size fixed. For NGC2768, the density profile of dust is the same as that of stars. The resulting τ_V of 0.3 corresponds to the dust mass of $8 \times 10^5 M_\odot$. The dust in the intracluster space is mainly heated by the hot gas, although the heating by the radiation field is important for the spectrum at the SMM wavelength and beyond. The diffuse dust emission of the Coma cluster can be reproduced with τ_V of 0.002, although this value is inconsistent with the extinction measurements. The cold dust that does not emit in the FIR may exist in the outer region of the Coma cluster.

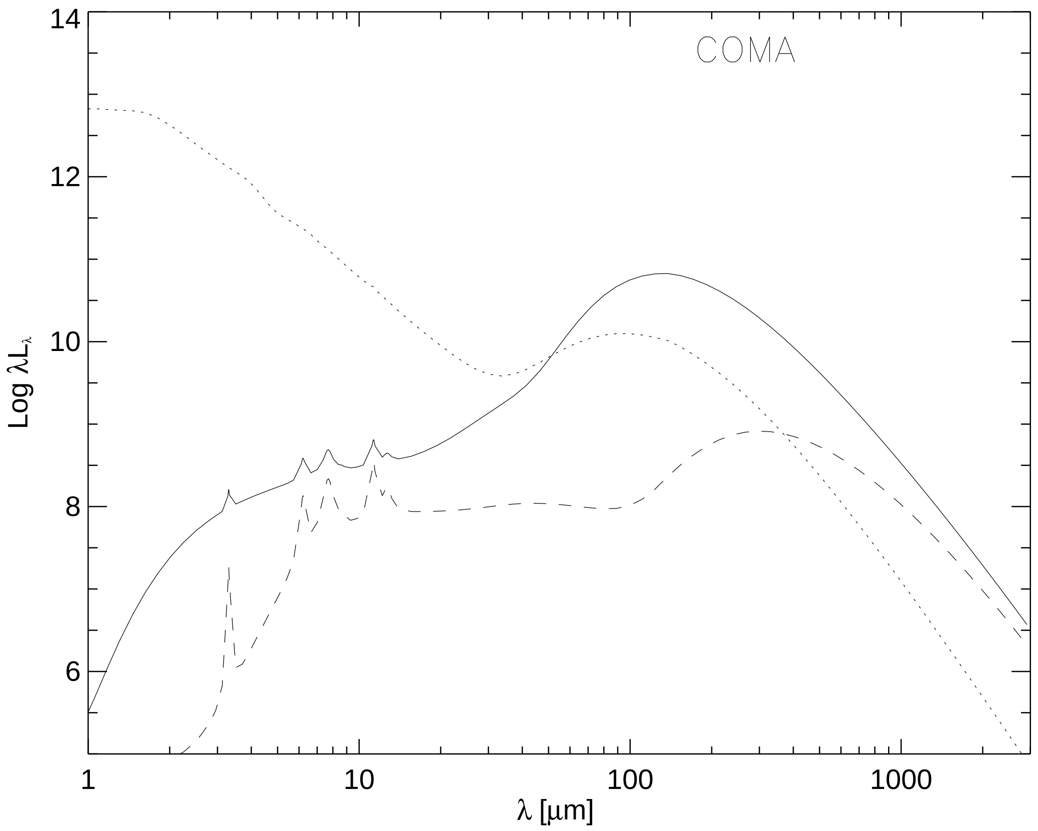

Fig. 7: SED of the Coma cluster. The solid curve shows the model corresponding to that in figure 7. Both the radiation field and hot gas are considered as the heating source of dust. Without hot gas, the SED darken and its peak wavelength increases depicted by the dashed curve. The dotted curve indicates the sum of SEDs of all galaxies in the Coma cluster. We assume that the Coma cluster consists of only elliptical galaxies.

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