Challenges in Panchromatic Modelling with
Next Generation Facilities
Proceedings IAU Symposium No. 341, 2018
M. Boquien, E. Lusso, C. Gruppioni & P. Tissera, eds.

doi:10.1017/S1743921319004794

A new galaxy Spectral Energy Distribution model with the evolution of dust consistent with chemical evolution

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Abstract. The spectral energy distribution (SED) model should treat the evolution of a galaxy from its birth. Dust in galaxies affects the formation and evolution of galaxies in various ways. For example, dust grains scatter and absorb stellar emitted ultraviolet (UV) photons and re-emit the radiation at infrared (IR) wavelengths. In this work, we construct a galaxy SED model based on our dust evolution model (Asano *et al.* 2013a,b, 2014) with a rigorous treatment of the chemical evolution. To reduce the computational cost, we adopt mega-grain approximation (MGA; Inoue, 2005). MGA regards a high density dusty region as a huge size (10 pc) dust grain for calculating dust scattering. In this approximation, we can solve the radiative transfer easily and provide SEDs and attenuation curves of galaxies. This model can be used to fit any galaxy in the wavelength range of 10 nm-3 mm.

Keywords. Panchromatic codes and modeling techniques

1. Introduction

Galaxy spectral energy distribution (SED) fitting is an important method which is frequently used for estimating several physical properties (e.g., star formation rate, stellar mass and dust mass). The main contributions of galaxy emission are separated into two components, stellar and dust. Dust absorbs UV light emitted by stars and re-emits as far-infrared (FIR) radiation. Therefore, dust in galaxies fundamentally determines the galaxy SED.

Some previous SED models (e.g., PEGASE; Fioc & Rocca-Volmerange, 1999) use an empirical dust model based on the properties of nearby galaxies. However, according to result from our new dust model (Asano model; Asano *et al.* 2013a,b, 2014), the dust-to-gas mass ratio suddenly rises up at a certain galaxy age. It implies that if we use such empirical dust mass distribution models to calculate distant galaxy SED, it might be inaccurate. Thus, we need to construct a new SED model based on Asano model.

2. Method

2.1. *Dust model*

We use a new dust evolution model proposed by Asano *et al.* It is a dust evolution model taking into account the chemical evolution and can predict the grain size distribution at each stage of the galaxy evolution. Figure 1 shows the most striking result which Asano model has shown. We clearly see a well-defined moment at which dust-to-gas mass ratio

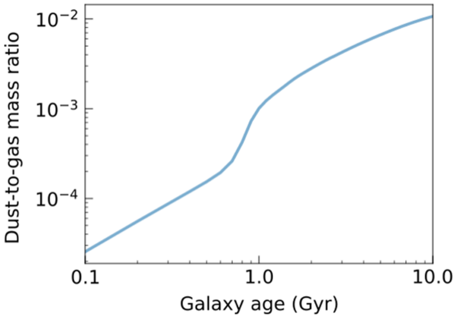

Figure 1. An example of the time dependence of the dust-to-gas mass ratio based on the Asano model. The dust-to-gas mass ratio suddenly rises up at early galaxy age. The age of the sudden increase depends on the supposed star formation history of a galaxy.

suddenly rises up. This age depends on star formation history. Figure 1 is a result for a Milky Way (MW)-like galaxy.

In this model, dust grains are treated as ten species (C, Si, Fe, FeS, Al_2O_3, $MgSiO_3$, Mg_2SiO_4, SiO_2, MgO, Fe_3O_4). However, since the detailed physical properties are not known for all the species, we divided them into two species for dust grains, carbon and silicate. We divide carbon grains into two subspecies, polycyclic aromatic hydrocarbons (PAH) and graphite, with a size boundary of 50 Å. PAHs are further subdivided into neutral and ionized PAHs. We regard the rest of the species as astronomical silicate. We use optical properties of PAHs, absorption coefficient, albedo, and asymmetry paramters, which were taken from Li & Draine (2001). Graphite and astronomical silicate grains properties were taken from Draine & Lee (1984a) and Laor & Draine (1993).

2.2. *Stellar emissions*

We use PEGASE for calculating stellar emissions except dust effects. PEGASE is an evolutionary SED model. We use the Salpeter (1955) initial mass function (IMF)

$$\phi(m) = Am^{-2.35}. \tag{2.1}$$

Where m is the stellar mass and A is a normalization constant defined from

$$\int_{0.1N_\odot}^{100M_\odot} m\phi(m)\mathrm{d}m = 1. \tag{2.2}$$

We use the Schmidt (1959) low to compute the star formation rate (SFR)

$$\psi(t) = \frac{M_{\mathrm{gas}}(t)}{\tau_{\mathrm{SF}}} \tag{2.3}$$

where $M_{\mathrm{gas}}(t)$ is the gas mass at time t and τ_{SF} is the star forming time scale.

2.3. *Mega-grain approximaion (MGA)*

We use two approximations to make the radiative transfer calculation faster. One is the mega-grain approximation (MGA; Inoue, 2005; Városi & Dwek 1999).

There are two thermally stable phases in the ISM, assuming thermal energy and chemical equilibria. One is the warm neutral medium (WNM) and the other is the cold neutral medium (CNM). We regard the WNM as a homogeneous inter-clump medium and CNM as a huge particle called a mega-grain. The size of mega-grain is set to be Jeans length $\sqrt{15p/4\pi G/\rho_{\mathrm{mg}}} = 10.4$ pc, where p is pressure of CNM, ρ_{mg} is mega-grain mass density and G is the gravitational constant. We replace the optical properties of normal grains (dust opacity k_d, albedo ω_d and asymmetry parameter g_d) with the effective values

$$\kappa_\mathrm{eff} = \kappa_\mathrm{mg} + \kappa_\mathrm{icm} \tag{2.4}$$

$$\omega_\mathrm{cl} = \frac{\omega_\mathrm{mg}\kappa_\mathrm{mg} + \omega_\mathrm{d}\kappa_\mathrm{mg}}{\kappa_\mathrm{eff}} \tag{2.5}$$

$$g_\mathrm{cl} = \frac{g_\mathrm{mg}\kappa_\mathrm{mg} + g_\mathrm{d}\kappa_\mathrm{mg}}{\kappa_\mathrm{eff}} \tag{2.6}$$

where $\kappa_\mathrm{eff}, \omega_\mathrm{eff}, g_\mathrm{eff}$ are the effective extinction coefficient per unit length, effective albedo, effective asymmetry parameter, $\kappa_\mathrm{icm} = k_\mathrm{d} D \rho_\mathrm{icm}$ is the extinction coefficient per unit length of the interclump medium, ω_cl and g_cl are the albedo and asymmetry parameter of a clump, respectively. We use MGA for solving the radiative transfer. However, in contrast we do not use MGA for treating dust re-emission, because the mega-grain has aout very large heat capacity, we use a normal dust grain for calculating dust temperature.

2.4. *One-dimensional galaxy approximation*

We suppose a one-dimensional plane-parallel geometry along the z-axis (Inoue, 2005). We put the gas-dust disk with a constant mean density at the mid-plane of the galaxy. This mid-plane contains mega-grains and young stars. Outside the gas-dust disk, we assume that there is no dust and only old stars diffusing from the mid-plane of the disk.

The optical depth is defined as $\mathrm{d}\tau = -\kappa_\mathrm{eff}\mathrm{d}z$ with $\tau = 0$ at $z = h_\mathrm{d}$. We assume effective optical parameters $\kappa_\mathrm{eff}, \omega_\mathrm{eff}, g_\mathrm{eff}$ are constant throughout the gas-dust disk. In this approximation, the radiative transfer equation is written by

$$\mu \frac{\mathrm{d}I(\tau,\mu)}{\mathrm{d}\tau} = S(\tau,\mu) - I(\tau,\mu) \tag{2.7}$$

where I is the intensity, μ is the cosine of the angle between the ray and the z-axis and S is the source function given by

$$S(\tau,\mu) = \eta_*(\tau)/\kappa_\mathrm{eff} + \omega_\mathrm{eff} \int_{-1}^{1} I(\tau,\mu')\Phi(g_\mathrm{eff},\mu,\mu')\mathrm{d}\mu' \tag{2.8}$$

where η_* is the stellar emissivity and Φ is the scattering phase function. We use the Henyey-Greenstein phase function (Henyey & Greenstein, 1941).

3. Result

Figure 2 shows one of the result of our SED model. The vertical axis represents galaxy luminosity times wavelength in units of solar luminosity per solar mass. Galaxy properties (e.g. total mass, star formation rate, disk radius and disk height) are fixed to the value corresponding to the face on ($\mu = 1$) MW-like galaxy at the age 10 Gyr.

4. Discussion

Figure 3 shows SED model at each galaxy age. 10 Gyr is same as figure 2. At short wavelengths, the emission of an old galaxy is more attenuated than for a young galaxy with increasing dust mass increasing. The FIR luminosity is very low at 100 Myr and becomes strong as time pass. However, we find the luminosity decreasing with elapsed time from 1 Gyr to 10 Gyr. It is affected by decreasing stellar luminosity which is the source of dust heating.

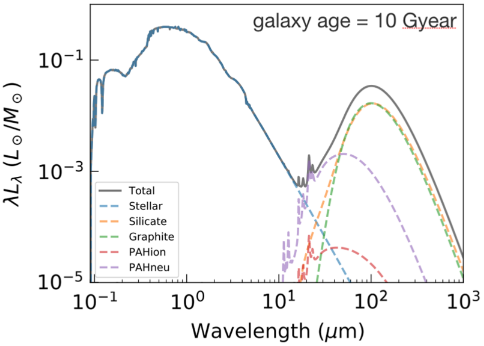

Figure 2. Example of our galaxy SED model. Parameters are fixed to MW ones. The black solid line represents the total galaxy emission, the blue dashed line is stellar emission, and others are the dust emission. This galaxy age is 10 Gyr.

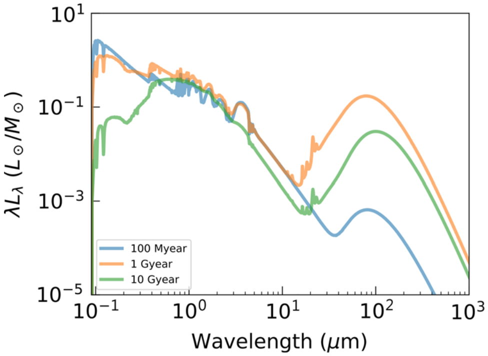

Figure 3. Example of SED models at each galaxy age. The blue, orange and green lines represent ages of 100 Myr, 1 Gyr and 10 Gyr.

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Discussion

Buat: On your resulting SEDs it seems that a UV absorption at 200 nm is still observed at 1 and 10 Gyr. Is the UV bump always present in your attenuation curves?

Nishida: The attenuation curve starts from a “gray” extinction, without a strong wavelength dependence at short wavelengths. Then it starts to steepen, and the bump emerges along with the increase of small dust grains. Later on, after 10 Gyrs, the curve becomes gradually flatter again and the bump weakens.

Galliano: Have you benchmarked your stochastic heating code? You could, for instance, compare your temperature distribution to these shown by Draine (2003). My question is motivated by the fact that your mid-infrared spectral energy distributions do not look right. It looks like your grains are not fluctuating to high enough temperatures.

Nishida: Indeed our mid-infrared spectral energy distributions seem to be weak. Grains are not heating to temperatures high enough. We have not made a benchmark test yet. We will do it and present tuned parameters for the Milky Way.