On properties of interstellar dust responsible for steep extinction curves measured toward Type Ia supernovae

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Abstract

The extinction laws along lines of sight to Type Ia supernovae (SNe Ia) are powerful probes that provide us with key clues to the properties of interstellar dust in external galaxies. It has been known, however, that the extinction curves toward SNe Ia are very steep with unusually low total-to-selective extinction ratios of Rv = 1.0-2.5. In order to reveal the properties of interstellar dust that causes such unusual extinction laws, we search for physical dust models that lead to good fits to the extinction curves obtained from the empirical formula by Cardelli et al. (1989) with Rv = 2.0, 1.5, and 1.0. In the fitting calculations, we apply a graphite-silicate dust model and consider two grain size distributions of power-law and lognormal functions.

We find that the steep extinction curves with Rv = 2.0, 1.5, and 1.0 can be reasonably explained even by the simple power-law dust models with a fixed index of -3.5 by taking the maximum cut-off radii of 0.13 µm, 0.094 µm, and 0.057 µm, respectively. These maximum cut-off radii are smaller than 0.24 µm considered valid in the Milky Way, clearly demonstrating that the interstellar dust responsible for steep extinction curves is biased to smaller sizes. We show that lognormal size distribution can also yield good fits to the extinction curves with Rv = 1.0-3.1 by adopting very small peak radius and large standard deviation of the distribution.

○ Extinction curves and CCM formula

- **Extinction curves ($A\lambda/Av$)**
  - wavelength dependence of UV-to-NIR extinction caused by interstellar dust

➜ powerful tool to know composition and size distribution of dust grains

- **CCM formula** (Cardelli, Clayton, Mathis 1989)
  - describes variety of extinction curves in the Milky Way (MW) through

$$R_V = A_V / E(B - V)$$

➜ Rv = 2.2-6.0 depending on sightlines

➜ Rv = 3.1 for average extinction curve

- **Classical dust model in the MW**
  - two components of graphite & silicate
  - power-law size distribution: $n(a) \propto a^{-q}$

$q = 3.5$, a_{max}~0.25 µm, a_{min}~0.005 µm (Mathis, Rumple, & Nordsieck 1977)

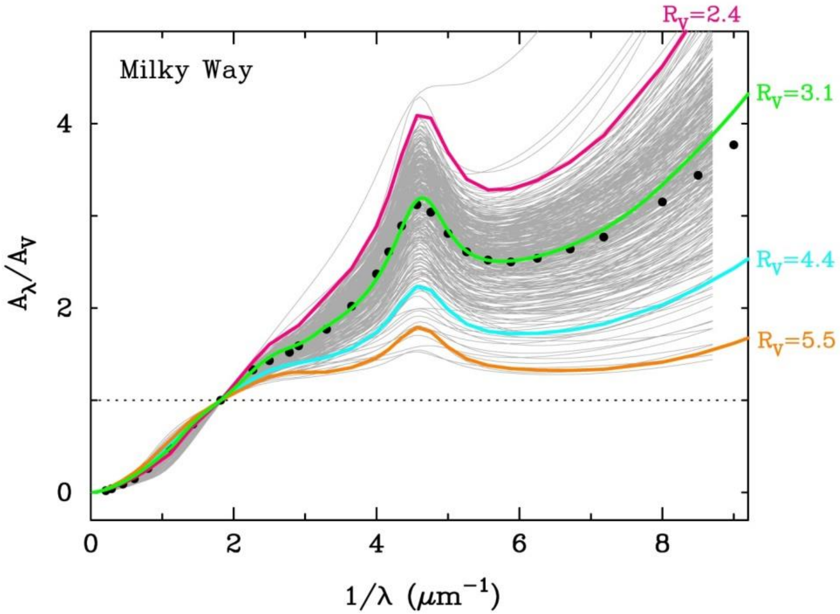


Figure 1;
UV-to-NIR extinction curves measured along different lines of sight in the MW (gray curves, Fitzpatrick & Massa 2007). The black circles indicates the MW average extinction curves. The four colored curves show the extinction curves calculated with the CCM formula for Rv = 2.4, 3.1, 4.4, and 5.5.

○ Extinction laws toward SNe Ia

- **Type Ia supernovae (SNe Ia)**
  - **thermonuclear explosion of a WD**
  - **discovered in all types of galaxies**
    (star-forming, elliptical, irregular etc…)
  - **used as cosmic standard candles**

ideal targets to probe the extinction (dust) properties in external galaxies

However, the values of Rv measured for SNe Ia are very low (Rv ~ 1.0-2.5), which never appear toward any lines of sight in the MW

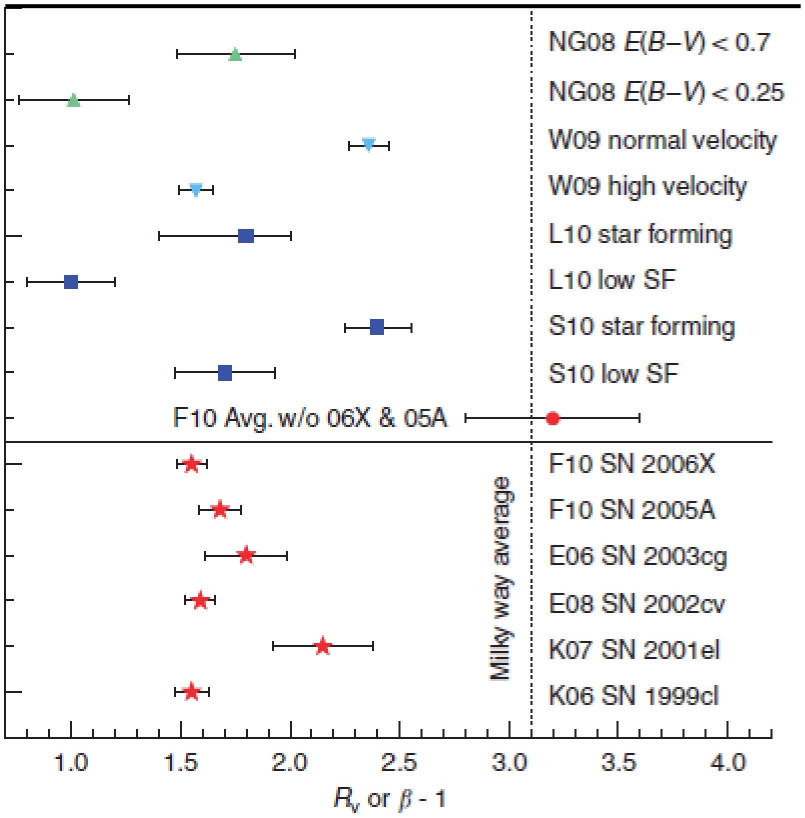


Figure 2; (taken from Howell 2011)
Rv values toward SNe Ia derived from a variety of samples and techniques. The cyan and blue points indicates the average values obtained from ensembles of SNe Ia, while the red ones show the Rv estimated on the basis of SEDs of individual SNe Ia.

○ Aim of this study and dust model

What properties of dust cause such steep extinction curves?

We perform the fitting calculations to the extinction curves with Rv = 1.0-2.0 by applying a graphite-silicate dust model

➜ two function forms for grain size distribution

(1) power-law distribution

$$n_j(a) = C_j a^{-q_j}$$

(2) lognormal distribution

$$n_j(a) = \frac{C_j}{\sqrt{2\pi} a \gamma_j} \exp\left[- \frac{(\ln a - \ln a_{0,j})^2}{2\gamma_j^2} \right]$$

where $C_j = m_j \left(\frac{4\pi\rho_j}{3} \int_{a_{\min,j}}^{a_{\max,j}} a^3 f_j(a) da \right)^{-1} = \frac{m_j}{X_j},$

➜ goodness of fitting to the extinction data

$$\chi_1^2 = \frac{1}{N_{\rm data} - N_{\rm para}} \sum_i^{N_{\rm data}} (y_{{\rm CCM},i} - y_{{\rm cal},i})^2 .$$

$y_{{\rm CCM},i}$ **: data of extinction Aλi/Av derived from the CCM formula at photometric bands**

○ Results for power-law size distribution

・ Best-fits for Model 1 with q = 3.5 and $a_{max,gra} = a_{max,sil}$

➜ a_{max} = 0.13, 0.094, 0.057 μm for Rv = 2.0, 1.5, 1.0
(i.e., smaller a_{max} for steeper extinction curve)

➜ Fits for Rv = 2.0 and 1.5 are good (solid lines in Fig. 3)

・ Best-fits for Model 2 with a_{max} = 0.25 μm and $q_{gra} = q_{sil}$

➜ q = 4.05, 4.40, 5.08 for Rv = 2.0, 1.5, 1.0
(i.e., larger q for steeper extinction curves)

➜ Fits for Rv = 1.5 and 1.0 are poor (dashed lines in Fig. 3)

The simplest power-law size distributions with q = 3.5 account for the entire shapes of steep extinction curves with Rv = 1.0-2.0 by taking a_{max} = 0.06-0.13 μm.

○ Extinction curves from power-law model

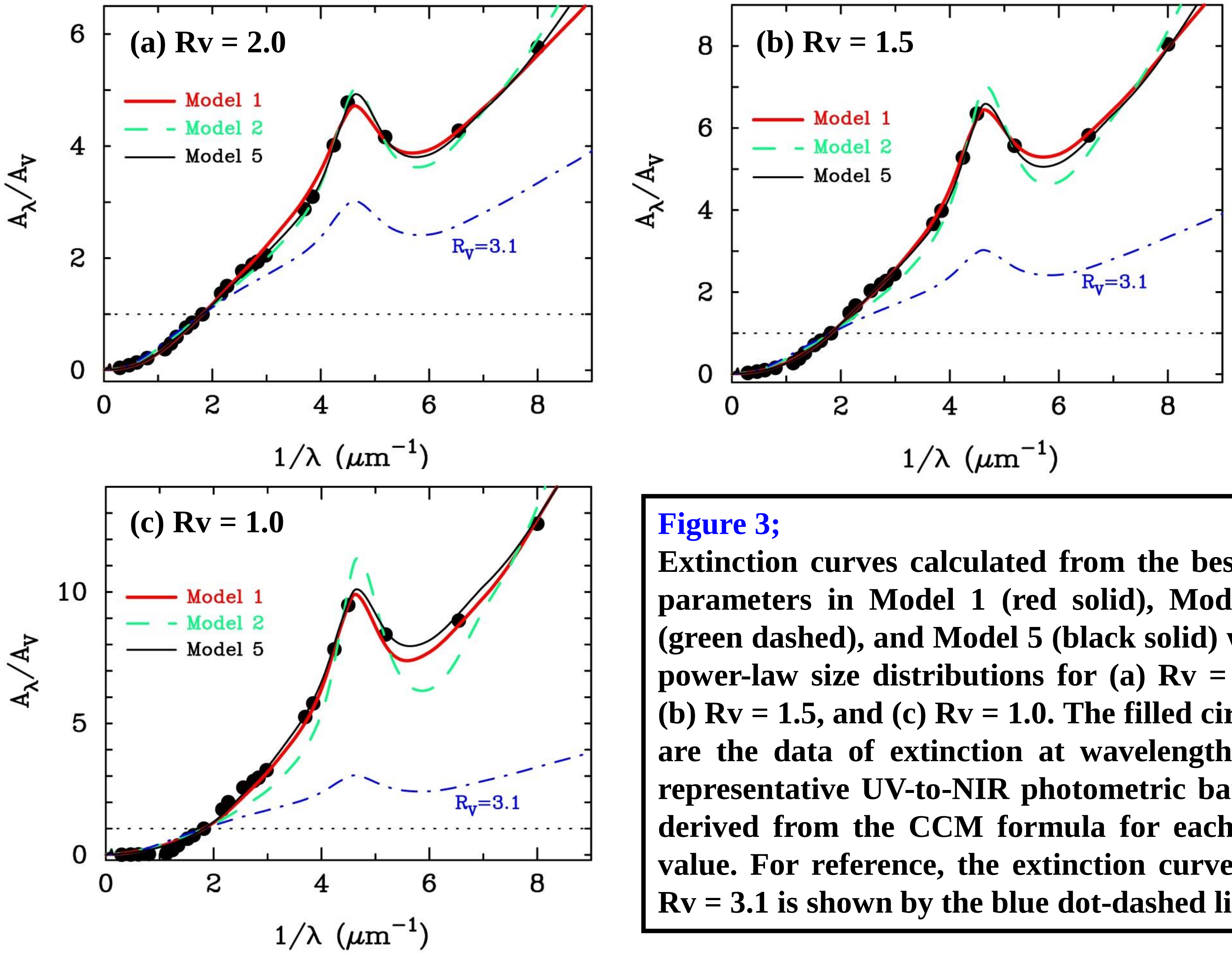
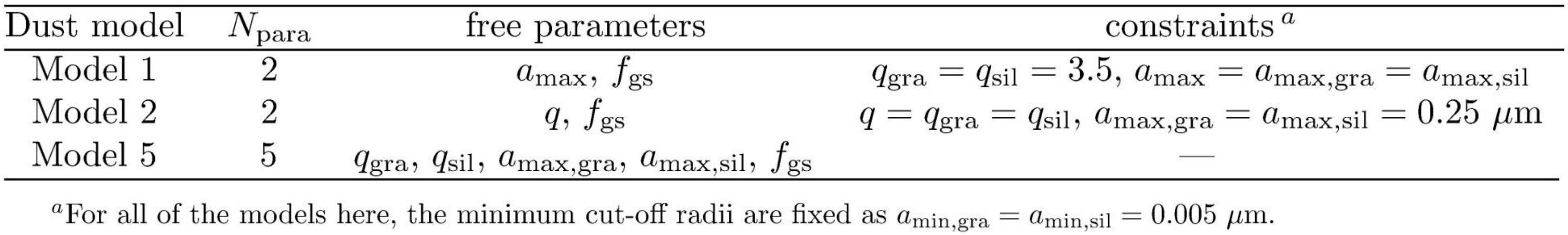


Figure 3;

Extinction curves calculated from the best-fit parameters in Model 1 (red solid), Model 2 (green dashed), and Model 5 (black solid) with power-law size distributions for (a) Rv = 2.0, (b) Rv = 1.5, and (c) Rv = 1.0. The filled circles are the data of extinction at wavelengths of representative UV-to-NIR photometric bands, derived from the CCM formula for each Rv value. For reference, the extinction curve for Rv = 3.1 is shown by the blue dot-dashed line.

○ Best-fit parameters for power-law model

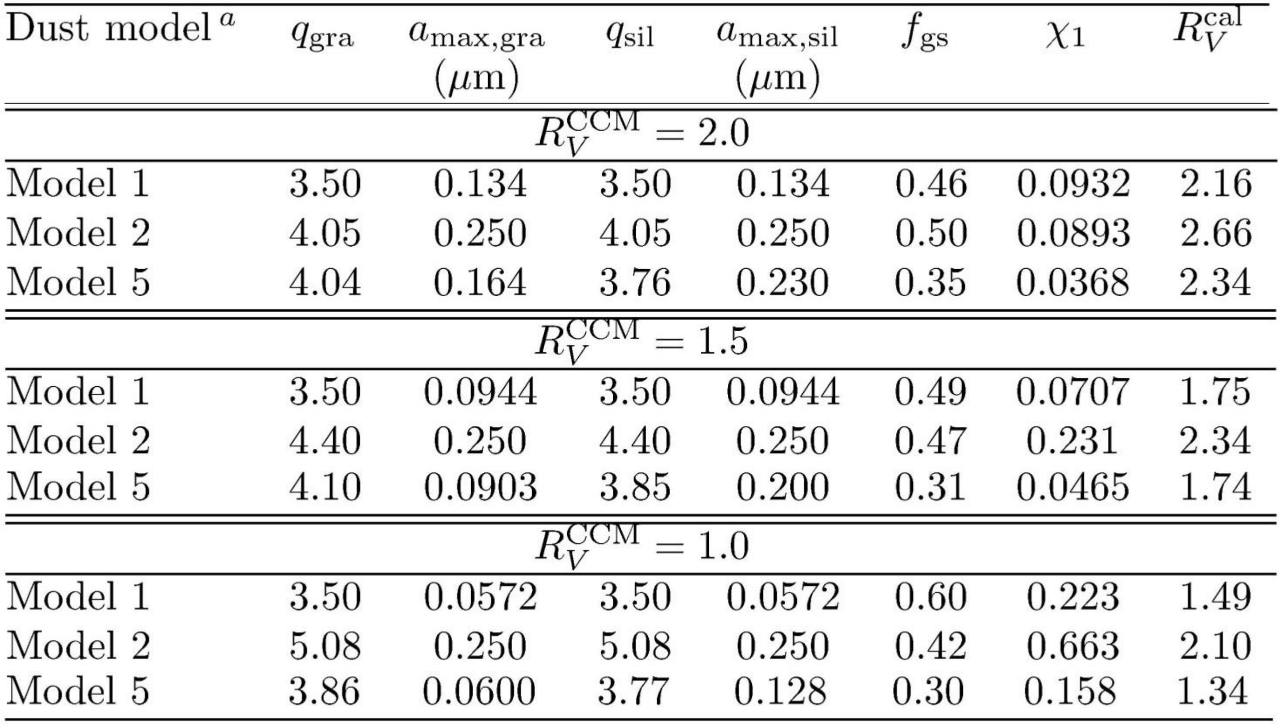
Table 1 : Dust models with power-law size distributions and their parameter sets.



Dust model	$N_{\rm para}$	free parameters	constraints [a]
Model 1	2	$a_{\rm max}$, $f_{\rm gs}$	$q_{\rm gra} = q_{\rm sil} = 3.5$, $a_{\rm max} = a_{\rm max,gra} = a_{\rm max,sil}$
Model 2	2	q, $f_{\rm gs}$	$q = q_{\rm gra} = q_{\rm sil}$, $a_{\rm max,gra} = a_{\rm max,sil} = 0.25$ μm
Model 5	5	$q_{\rm gra}$, $q_{\rm sil}$, $a_{\rm max,gra}$, $a_{\rm max,sil}$, $f_{\rm gs}$	—

[a] For all of the models here, the minimum cut-off radii are fixed as $a_{\rm min,gra} = a_{\rm min,sil} = 0.005$ μm.

Table 2 : A set of the best-fit parameters obtained for dust models with power-law size distributions.



Dust model [a]	$q_{\rm gra}$	$a_{\rm max,gra}$ (μm)	$q_{\rm sil}$	$a_{\rm max,sil}$ (μm)	$f_{\rm gs}$	χ_1	$R_V^{\rm cal}$
$R_V^{\rm CCM} = 2.0$							
Model 1	3.50	0.134	3.50	0.134	0.46	0.0932	2.16
Model 2	4.05	0.250	4.05	0.250	0.50	0.0893	2.66
Model 5	4.04	0.164	3.76	0.230	0.35	0.0368	2.34
$R_V^{\rm CCM} = 1.5$							
Model 1	3.50	0.0944	3.50	0.0944	0.49	0.0707	1.75
Model 2	4.40	0.250	4.40	0.250	0.47	0.231	2.34
Model 5	4.10	0.0903	3.85	0.200	0.31	0.0465	1.74
$R_V^{\rm CCM} = 1.0$							
Model 1	3.50	0.0572	3.50	0.0572	0.60	0.223	1.49
Model 2	5.08	0.250	5.08	0.250	0.42	0.663	2.10
Model 5	3.86	0.0600	3.77	0.128	0.30	0.158	1.34

○ Results for lognormal size distribution

- **Best-fits for Model 1s with $\gamma_j = 0.5$**

➜ $a_{0,j}$ = 0.013-0.024 μm for Rv = 1.0-2.0
(i.e., smaller $a_{0,j}$ for steeper extinction curve)

➜ Fits for Rv = 2.0 and 1.5 are poor (dashed lines in Fig. 4)

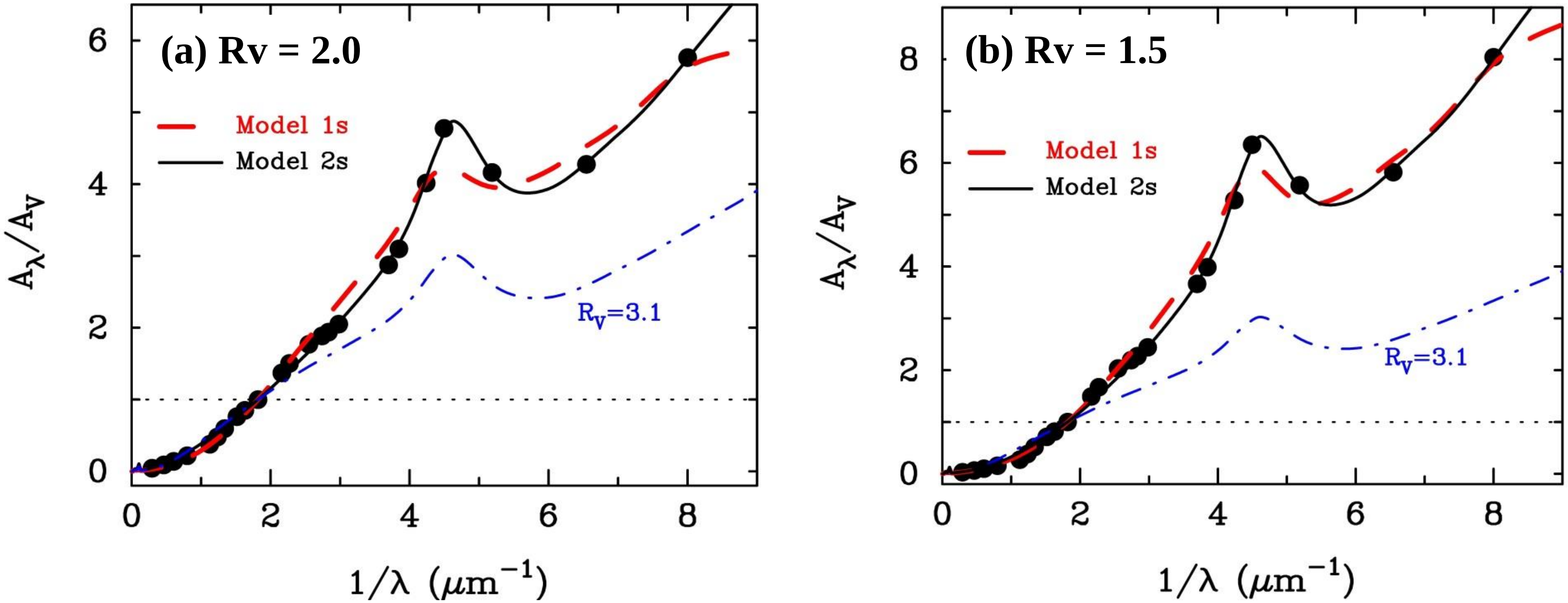
- **Best-fits for Model 2s with no fixed parameter**

➜ $a_{0,j} < \sim 3\text{x}10^{-3}$ μm and $\gamma_j \sim 1.0$ for Rv = 1.5 and 2.0
which appears an exponential-like distribution (Fig. 5)

➜ Fits for Rv = 2.0 and 1.5 are good (solid lines in Fig. 4)

The lognormal size distribution can lead to good fits to the CCM extinction curves with Rv = 1.0-2.0 by taking the appropriate sets of $a_{0,j}$ and γ_j.

○ Extinction curves from lognormal model



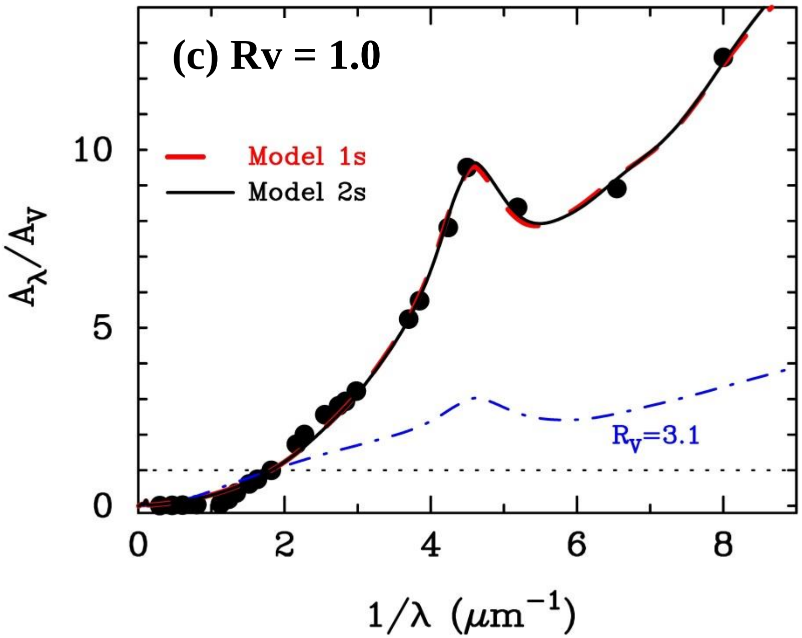


Figure 4;
Extinction curves calculated from the best-fit parameters in Model 1s (red dashed) and Model 2s (black solid) with lognormal size distributions for (a) Rv = 2.0, (b) Rv = 1.5, and (c) Rv = 1.0. The filled circles are the data of extinction at wavelengths of representative UV-to-NIR photometric bands, derived from the CCM formula for each Rv value. For reference, the extinction curve for Rv = 3.1 is shown by the blue dot-dashed line.

○ Best-fit parameters for lognormal model

Table 3 : Dust models with lognormal size distributions and their parameter sets.

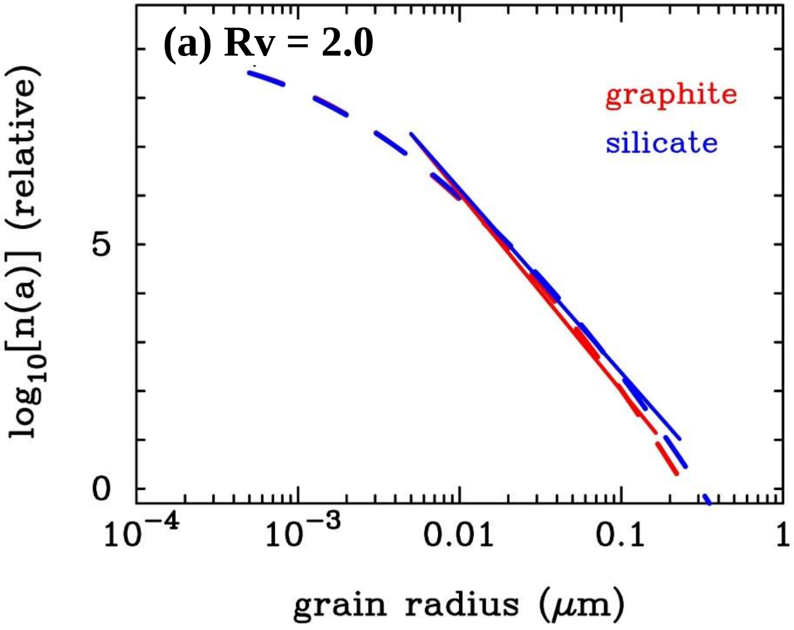
Dust model	$N_{\rm para}$	free parameters	constraints [a]
Model 1s	3	$a_{0,{\rm gra}}$, $a_{0,{\rm sil}}$, $f_{\rm gs}$	$\gamma_{\rm gra} = \gamma_{\rm sil} = 0.5$
Model 5s	5	$a_{0,{\rm gra}}$, $a_{0,{\rm sil}}$, $\gamma_{\rm gra}$, $\gamma_{\rm sil}$, $f_{\rm gs}$	—

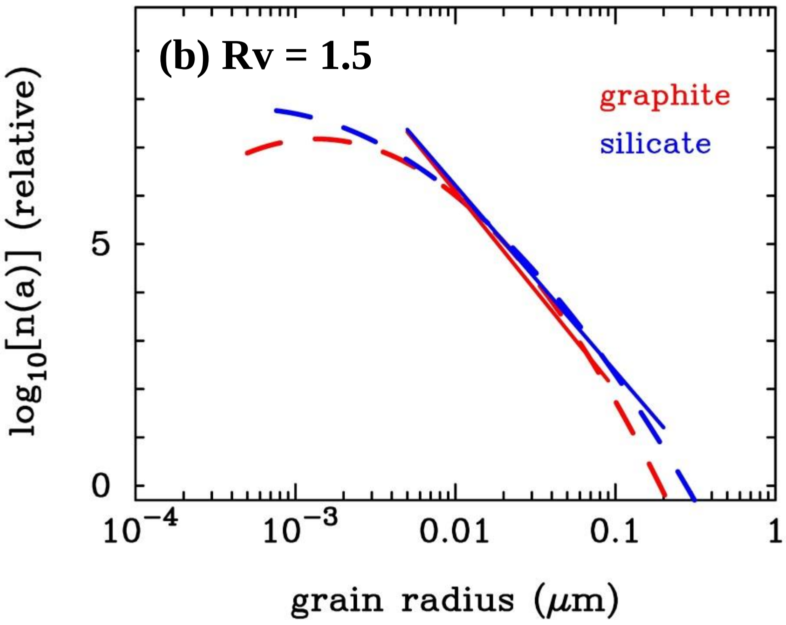
[a] For the models with lognormal size distributions, the maximum and minimum cut-off radii are fixed to be $a_{\rm max,gra} = a_{\rm max,sil} = 10$ μm and $a_{\rm min,gra} = a_{\rm min,sil} = 5 \times 10^{-4}$ μm, respectively.

Table 4 : A set of the best-fit parameters obtained for dust models with lognormal size distributions.

Dust model [a]	$\gamma_{\rm gra}$	$a_{0,{\rm gra}}$ (μm)	$\gamma_{\rm sil}$	$a_{0,{\rm sil}}$ (μm)	$f_{\rm gs}$	χ_1	$R_V^{\rm cal}$
$R_V^{\rm CCM} = 2.0$							
Model 1s	0.50	0.0238	0.50	0.0201	0.78	0.208	1.87
Model 5s	1.18	5.60×10^{-4}	1.25	5.00×10^{-4}	0.42	0.0608	2.48
$R_V^{\rm CCM} = 1.5$							
Model 1s	0.50	0.0186	0.50	0.0185	0.69	0.220	1.61
Model 5s	0.86	2.84×10^{-3}	1.06	1.48×10^{-3}	0.38	0.0890	1.95
$R_V^{\rm CCM} = 1.0$							
Model 1s	0.50	0.0127	0.50	0.0172	0.54	0.239	1.49
Model 5s	0.50	0.0114	0.71	8.63×10^{-3}	0.39	0.232	1.50

○ Examples of grain size distributions





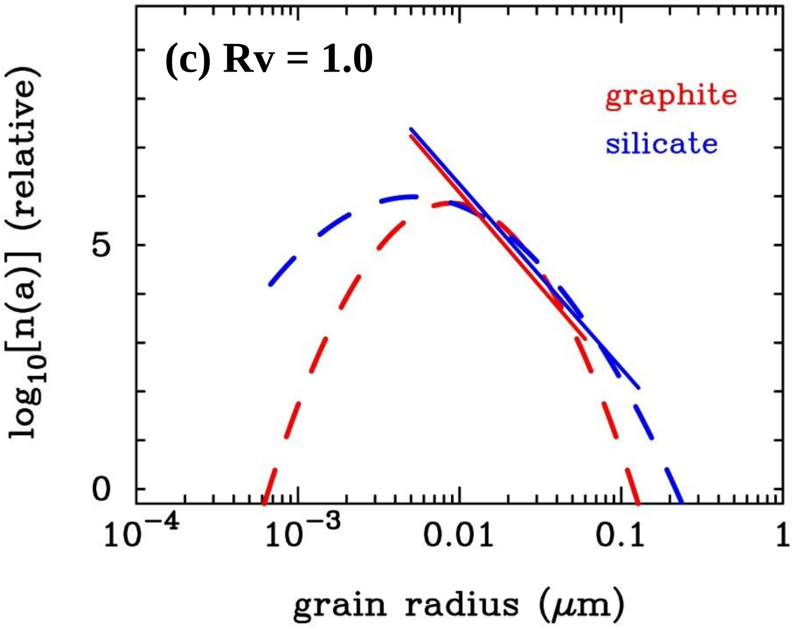


Figure 5;
Grain size distribution that lead to the best-fit to the extinction curves with (a) Rv = 2.0, (b) Rv = 1.5, and (c) Rv = 1.0. The solid lines show the power-law size distributions obtained from Model 5, while the dashed lines indicates the lognormal size distributions obtained from Model 2s. Graphite and silicate are drawn in red and blue, respectively.

Summary

1) **Many observational studies of Type Ia supernovae suggest that the Rv values measured toward SNe Ia are significantly low (Rv ~ 1.0-2.5), compared with Rv = 3.1 in the MW**

2) **The steeper extinction curves described by Rv = 1.0-2.5 are reproduced by the dust models whose size distributions are skewed to smaller radii than that in the MW.**

a) Power-law size distribution

➜ Maximum cut-off radius (a_{max}) is an important quantity to describe the variety of extinction curves, and if the power index is fixed to be q = 3.5, a_{max} = 0.06-0.13 μm is required.

b) Lognormal size distribution

➜ Very small peak radius $a_{0,j}$ and large standard deviation γ_j are needed to yield good fits to the steep extinction curves.