Properties and Alignment of Interstellar Dust Grains toward Type Ia Supernovae with Anomalous Polarization Curves

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Abstract
Recent photometric and polarimetric observations of Type Ia supernovae (SNe Ia) show unusually low total-to-selective extinction ratios ($R_V < 2$) and wavelengths of maximum polarization ($\lambda_{\text{max}} < 0.4 \mu m$) for several SNe Ia, which indicates peculiar properties of interstellar (IS) dust in the SN-hosted galaxies and/or the presence of circumstellar (CS) dust. In this paper, we use an inversion technique to infer the best-fit grain size distribution and the alignment function of interstellar grains along the lines of sight toward four SNe Ia with anomalous extinction and polarization data (SN 1986G, SN 2006X, SN 2008fp, and SN 2014J). We find that to reproduce low values of $R_V$, a significant enhancement in the mass of small grains of radius $a < 0.1 \mu m$ is required. For SN 2014J, a simultaneous fit to its observed extinction and polarization is unsuccessful if all the data are attributed to IS dust (model 1), but a good fit is obtained when accounting for the contribution of CS dust (model 2). For SN 2008fp, our best-fit results for model 1 show that in order to reproduce an extreme value of $\lambda_{\text{max}} \sim 0.15 \mu m$, small silicate grains must be aligned as efficiently as big grains. For this case, we suggest that strong radiation from the SN can induce efficient alignment of small grains in a nearby intervening molecular cloud via the radiative torque (RAT) mechanism. The resulting time dependence polarization from this RAT alignment model can be tested by observing at ultraviolet wavelengths.

Key words: dust, extinction – polarization – supernovae: general – supernovae: individual (SN 1986G, SN 2006X, SN 2008fp, SN 2014J)

1. Introduction
Type Ia supernovae (SNe Ia) have been used as standard candles to measure the expansion of the universe owing to their stable intrinsic luminosity (Riess et al. 1998). Recently, a new avenue appears in using SNe Ia to study properties of dust in the interstellar medium (ISM) of distant galaxies (Nobili & Goobar 2008; Brown et al. 2015; Foley et al. 2014). This advancement is based on the strong dependence of peak luminosity on the reddening of SNe Ia by dust extinction (see Phillips et al. 2013).

Photometric observations of SNe Ia demonstrate peculiar dust properties with unprecedented low visual-to-selective extinction ratio $R_V = A_V / E_{B-V}$, where $A_V$ is the optical extinction and $E_{B-V}$ is the reddening (i.e., color excess). For instance, using data from 80 SNe Ia with considerable reddening (i.e., $E_{B-V} < 0.87$ mag), Nobili & Goobar (2008) report an unusually low value of $R_V \sim 1.75$ (see also Phillips et al. 2013), much lower than the typical value $R_V \sim 3.1$ for interstellar grains in the Milky Way. Recently, using data from UV to near-IR ($\lambda \sim 0.2–2 \mu m$) from the Hubble Space Telescope and Swift satellites, Amanullah et al. (2015) present a diversity in extinction curves, with $R_V$ ranging from 1.4 to 3 (see also Wang et al. 2012). Unprecedentedly low values of $R_V$ toward numerous SNe Ia are attributed to the scattering by circumstellar (CS) dust (see, e.g., Goobar 2008). Numerous authors, however, suggest that the low values of $R_V$ are due to the enhancement in the relative abundance of small grains of interstellar (IS) dust in the host galaxy (see Phillips et al. 2013). Thus, it is interesting to infer the size distribution of interstellar grains that reproduce such low values of $R_V$.

Polarimetric studies of SNe Ia have opened a new window into probing dust properties and grain alignment in the galaxies because the intrinsic polarization of SN light is negligible (see Wang & Wheeler 2008, for a review). Four SNe Ia with high-quality polarization data (SN 1986G, SN 2006X, SN 2008fp, and SN 2014J) exhibit anomalous polarization curves that rise toward UV wavelengths (Kawabata et al. 2014; Patat et al. 2015). Fitting the observational data with the typical ISM polarization law (Serkowski law) yields an anomalous value of peak wavelength ($\lambda_{\text{max}} < 0.2 \mu m$) for SN 2008fp and SN 2014J, which is much lower than the typical value $\lambda_{\text{max}} \sim 0.55 \mu m$ in the Galaxy. For comparison, available data for Galactic polarization show the lowest peak wavelengths $\lambda_{\text{max}} = 0.33 \mu m$ and $0.35 \mu m$ for Cyg OB2 No. 10 and 12, respectively (Whittet et al. 1992), and $\lambda_{\text{max}} < 0.35 \mu m$ for HD 193682 (Anderson et al. 1996).

The question of which origin (IS dust or CS dust) for these anomalous values of $R_V$ and $\lambda_{\text{max}}$ remains unclear, and addressing this question has important implications for better understanding the progenitors of SNe Ia. If IS dust is important, as suggested in previous studies (Phillips et al. 2013; Patat et al. 2015), the anomalous values could reflect peculiar properties of dust and alignment of grains in intervening clouds along the lines of sight (LOSs) to SNe or perhaps in the average IS dust of the hosted galaxies (Phillips et al. 2013; Patat et al. 2015). In this paper, we will use an inversion technique (Section 4) to infer the best-fit grain size distribution and the alignment function, in order to understand dust properties and the alignment underlying the anomalous features.

The structure of the paper is as follows. In Section 2 we present observational data for the selected SNe Ia compiled from the literature. Section 3 is devoted to present theoretical
models of extinction and polarization and observational constraints. In Section 4 we briefly describe our inversion technique and obtained results. Extended discussions on dust properties and grain alignment mechanisms responsible for the anomalous extinction and polarization are presented in Section 5. A short summary is given in Section 6.

2. Observed Extinction and Polarization Data

2.1. Extinction and Polarization of Starlight in the Milky Way

Interstellar dust causes extinction of starlight, which can be described by the Cardelli et al. (1989) (CCM) extinction law with $R_V \sim 3.1$. In addition, the alignment of nonspherical grains with interstellar magnetic fields produces differential extinction of starlight, resulting in starlight polarization, and thermal emission from aligned dust grains becomes linearly polarized (see Andersson et al. 2015; Lazarian et al. 2015, hereafter LAH15, for latest reviews).

The wavelength-dependence polarization (hereafter polarization curve) induced by IS dust is approximately described by the Serkowski law (Serkowski et al. 1975):

$$P_{\text{is}}(\lambda) = P_{\text{max}} \exp \left[ -K \ln^2 \left( \frac{\lambda}{\lambda_{\text{max}}} \right) \right],$$

where $P_{\text{max}}$ is the maximum polarization at wavelength $\lambda_{\text{max}}$, and $K$ is a parameter related to the width of the Serkowski law (Wilking et al. 1980). For the Galaxy, $\lambda_{\text{max}} \sim 0.55 \mu m$, although some LOSs exhibit lower $\lambda_{\text{max}}$. But to date, the low values of $\lambda_{\text{max}} < 0.3 \mu m$ have not been detected (see Andersson & Potter 2007), except a few LOSs toward SNe Ia mentioned here.

2.2. SN 1986G and SN 2006X

SN 1986G exploded in a dust lane in the host galaxy NGC 5128 (Cen A), which was found to have at least a dozen distinct clouds along the LOS (D’Odorico et al. 1989; Cristiani et al. 1992). Optical and near-IR photometric observations show that the extinction of SN 1986G can be described by the CCM law with $R_V = 2.57$ (see Phillips et al. 2013). Polarimetric measurements were first reported in Hough et al. (1987), in which the polarization curve is well fitted by the Serkowski law with $\lambda_{\text{max}} = 0.43 \mu m$. Hough et al. (1987) suggested that the average size of dust grains in Cen A is smaller than in the Milky Way. It was also suggested that interstellar grains in the dust lane are aligned with the local magnetic field, but with the alignment efficiency lower than that in the Milky Way.

SN 2006X exploded within or behind the disk of NGC 4321, a normal galaxy in the Virgo Cluster. Photometric observations in the optical and near-infrared by Wang et al. (2008a) reveal an unusually low value of $R_V \approx 1.5$, and spectropolarimetric data (Patat et al. 2009) show a low value of $\lambda_{\text{max}} \sim 0.365 \mu m$. It was suggested that the bulk of the polarization is produced by aligned grains within a single dense molecular cloud in the host galaxy ISM (Cox & Patat 2008; Phillips et al. 2013; Patat et al. 2015). Therefore, for SN 1986G and SN 2006X, in the following, we assume that the entire extinction and polarization are produced by IS dust. Although some small amount of CS dust is detected toward these SNe, its contribution is negligible in terms of reddening and polarization.

2.3. SN 2008fp and SN 2014J

2.3.1. Anomalous Values of $R_V$ and $\lambda_{\text{max}}$

SN 2008fp is located in the host galaxy ESO 428-G14, a peculiar galaxy with an active nucleus. Similar to SN 2006X, SN 2008fp exhibits an extreme value of $R_V \sim 1.2$ (Phillips et al. 2013; Cox & Patat 2014). Its polarization data also demonstrate an anomalous value of $\lambda_{\text{max}} \sim 0.15 \mu m$ (Cox & Patat 2014). It is believed that the extinction and polarization for SN 2008fp are mainly produced by IS dust owing to the lack of variability in the absorption-line profile and strong CN interstellar absorption features (Cox & Patat 2014).

SN 2014J is located in the host galaxy NGC 3034 (M82), which was discovered accidentally by a group of students (Fossey et al. 2014). Photometric observations using Swift near-UV and optical–near-IR data by Brown et al. (2015) show that the reddening of SN 2014J can be best fitted by the CCM law with $R_V = 1.4$ (see also Welty et al. 2014; Amanullah et al. 2015). Polarimetric observations show an even more extreme value of $\lambda_{\text{max}} = 0.05 \mu m$ (Patat et al. 2015; see also Kawabata et al. 2014).

We note that the solid evidence for the peak wavelength is missing, and the values of $\lambda_{\text{max}}$ reported in Patat et al. (2015) are upper limits. Thus, the applicability of the empirical Serkowski law outside of the visible range is debatable. To explore dust properties and grain alignment for the wide range of grain size, especially for small grains that mostly contribute to UV extinction and polarization, we still extrapolate the data to UV wavelengths owing to the lack of real observations in the UV.

Foley et al. (2014) obtained similar fits for the two different models with and without CS dust. For the former model, they show that the best-fit models for the extinction toward SN 2014J require equal reddening contributions from both CS and IS dust. Their best-fit parameters for the interstellar reddening are $R_V = 2.59$ and $E_{B-V} = 0.45$ mag (i.e., $A_V = 1.165$ mag), and CS dust contributes about half the extinction. On the other hand, appealing to the well-aligned polarization angles with the local spiral arms of the host galaxies and small variability before and after the maximum epoch, Patat et al. (2015) argued that IS dust is a dominant contribution to the observed polarization, although adding the contribution of CS dust, they obtained more reasonable values of $R_V$ and $\lambda_{\text{max}}$ for this case. It is noted that the LOS to SN 2014J shows a multitude (>20) of absorption systems (revealed by the Ca, Na, and K interstellar lines). As the host galaxy is seen almost edge-on, it is natural to expect that the LOS would intercept many intervening clouds. Unless we want a substantial fraction of those clouds (which have different velocities) to be very close to the SN, it is very hard to believe that up to 50% of the extinction is generated “locally,” and the same applies to polarization.

2.3.2. Two-component Extinction/Polarization Model

Due to uncertainty in the origin of anomalous $R_V$ and $\lambda_{\text{max}}$ in SN 2008fp and SN 2014J, we consider two models (model 1 and model 2). Model 1 assumes that all the extinction and polarization are produced by IS dust (one dust component), whereas model 2 considers two dust components (IS and CS dust) contributing to the observed data.
The observed extinction from both IS and CS dust is given by

\[ A_{\text{obs}}(\lambda) = A_{\text{IS}}(\lambda) + A_{\text{CS}}(\lambda), \]  

(2)

where \( A_{\text{IS}}(\lambda) \) is given by the CCM law, and the latter is a power law (Goobar 2008):

\[ (A(\lambda)/A_V)_{\text{CS}} = 1 - \alpha + \alpha \left( \frac{0.55 \mu m}{\lambda} \right)^q, \]

(3)

where \( \alpha \) and \( q \) are free parameters.

Let \( f_{\text{cs}} \) be the fraction of the total observed visual extinction \( A_V \) contributed by CS dust. Then, we can obtain the following:

\[ A_{\text{CS}}(\lambda) = f_{\text{cs}} A_V \times (A(\lambda)/A_V)_{\text{CS}}, \]

(4)

\[ A_{\text{IS}}(\lambda) = (1 - f_{\text{cs}}) A_V \times (A(\lambda)/A_V)_{\text{IS}}. \]

(5)

Similarly, including the polarization due to Rayleigh scattering by CS dust (see Andersson et al. 2013, for details), the observed polarization is then equal to

\[ P_{\text{obs}}(\lambda) = P_{\text{IS}}(\lambda) + P_{\text{CS}} \left( \frac{\lambda}{0.4 \mu m} \right)^{-4}, \]

(6)

where \( P_{\text{IS}}(\lambda) \) is the polarization from IS dust (Equation (1)), and \( P_{\text{CS}} \) denotes the polarization due to Rayleigh scattering. Above, we have adopted the \(-4\) slope for the polarization by Rayleigh scattering, presumably due to Mie scattering by small grains and molecules. However, the precise slope of Rayleigh scattering is uncertain, depending on the source geometry and observation wavelength. Moreover, we have assumed that the interstellar polarization and scattering polarization are additive, which is only valid when the polarization directions from the two processes are aligned. There might be some special geometry of CS dust clouds that can satisfy these conditions, which is suggested in Section 5.3.

To infer the best-fit model parameters \( \alpha, q, f_{\text{cs}}, \) and \( R_V, \) we use the publicly available package lmfit-py\(^1\) to fit \( A_{\text{obs}}(\lambda) \) to the observed extinction. Similarly, we fit \( P_{\text{obs}}(\lambda) \) to the observed polarization to find \( P_{\text{cs}}, \lambda_{\text{max}}, P_{\text{max}}, \) and \( K. \) The error for the extinction is assigned to be 10%, and the polarization fit is interpolated from the real observational data.

Our fits using the two-component model return reasonable parameters with \( R_V \approx 2.2 \) for IS dust contributing \( A_V = 0.29 \) to the total observed extinction, \( \lambda_{\text{max}} = 0.41 \mu m, \) and \( K = 1.03 \) (see details in Figure 1 for SN 2008fp). We also rerun for SN 2014J and obtain a good fit with comparable parameters to those in previous works (Foley et al. 2014; Patat et al. 2015).

### 3. Dust Model and Observational Constraints

#### 3.1. Dust Model

We adopt a mixed-dust model consisting of astronomical silicate grains and graphite grains (see Weingartner & Draine 2001; Draine & Li 2007). Because graphite grains are unlikely to be aligned with the magnetic field (Chiar et al. 2006; see LAH15, for a review), we assume that only silicate grains are aligned while carbonaceous grains are randomly oriented. Oblate spheroidal grains with axial ratio \( r = 2 \) are considered.

The extinction of starlight induced by randomly oriented grains in units of magnitude is given by

\[ A(\lambda) = \sum_{j=sil,carb} 1.086 \int \int C_{\text{ext}}^j(a) \left( \frac{da}{da} \right) da dz, \]

(7)

where \( a \) is the effective grain size defined as the radius of an equivalent sphere of the same grain volume, \( da/da \) is the grain size distribution of dust component \( j, \) \( C_{\text{ext}} \) is the extinction cross section, and the integration is taken along the entire LOS \( z \).

The degree of polarization (in units of %) of starlight due to differential extinction by aligned grains along the LOS is computed by

\[ P(\lambda) = \sum_{j=sil} 100 \int \int \frac{1}{2} C_{\text{pol}}(a) f(j)(a) \left( \frac{da}{da} \right) da dz, \]

(8)

where \( C_{\text{pol}} \) is the polarization cross section, and \( f(j)(a) \) is the effective degree of grain alignment for dust component \( j \) with size \( a \) (hereafter alignment function). Here we take \( C_{\text{ext}} \) and

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\(^1\) http://cars9.uchicago.edu/software/python/lmfit/index.html
\[ C_{\text{pol}} \] computed for different grain sizes and wavelengths from Hoang et al. (2013).

### 3.2. Observational Constraints

#### 3.2.1. Gas-to-dust Ratio

The important constraint of the dust model is the gas-to-dust mass ratio, which ensures that the total gas mass relative to the total dust mass must be constrained by observations. The gas-to-dust mass ratio is usually represented through \( N_H/A_V \), where \( N_H \) is the gas column density. For the Galaxy, measurements give \( N_H/E_{B-V} = 5.8 \times 10^{21} \text{cm}^{-2} \text{mag}^{-1} \), which corresponds to \( N_H/A_V = 5.8 \times 10^{21} \text{cm}^{-2} \text{mag}^{-1}/R_0 \).

The gas-to-dust mass ratio for the SN 1986G-hosted galaxy is measured by Herschel (Parkin et al. 2012) and SINGS (Draine et al. 2007). The former provides an average gas-to-dust mass ratio of 103 ± 8, which is similar to that of our Galaxy. Therefore, we can take the same ratio of the Galaxy, \( N_H/E_{B-V} = 5.8 \times 10^{21} \text{cm}^{-2} \text{mag}^{-1} \), for the LOS to SN 1986G with \( E_{B-V} = 0.79 \text{mag} \). It is worth mentioning that D’Odorico et al. (1989) estimated \( N_H \sim 5 \times 10^{21} \text{cm}^{-2} \) for \( E_{B-V} = 0.9 \pm 0.1 \text{mag} \).

The reddening to SN 2006X is estimated to be \( E_{B-V} = 1.42 \pm 0.4 \text{mag} \), assuming that the Galactic foreground is equal to 0.026 mag. Observations for NGC 4321 in Draine et al. (2007) show that the dust-to-gas ratio is about two times higher than that of our Galaxy, with metallicity comparable to the solar abundance. Therefore, for SN 2006X, we assume \( N_H/A_V = 5.8 \times 10^{21} \text{cm}^{-2} \text{mag}^{-1}/2R_0 \), or \( N_H/E_{B-V} = 2.9 \times 10^{21} \text{cm}^{-2} \text{mag}^{-1} \) for \( R_V = 1.31 \).

For SN 2008fp, Cox & Patat (2014) estimated \( N(H_2) = 6.2^{+3.3}_{-2.11} \times 10^{20} \text{cm}^{-2} \) and \( N(H_2) = 7.2^{+4.5}_{-2.1} \times 10^{20} \text{cm}^{-2} \), which gives \( N_H = N(H_2) + 2N(H_2) = 2.1 \times 10^{21} \text{cm}^{-2} \). For model 1, we get \( N_H/A_V = 2.95 \times 10^{21} \text{cm}^{-2} \text{mag}^{-1} \) for \( A_V = 0.71 \text{mag} \). For \( R_V = 1.2 \), it yields \( N_H/E_{B-V} = 3.52 \times 10^{21} \text{cm}^{-2} \text{mag}^{-1} \), indicating that the dust-to-gas ratio in this galaxy is higher than that in the Galaxy. For model 2, in which the scattering by IS dust is included, the ratio becomes \( N_H/E_{B-V} = 1.6 \times 10^{22} \text{cm}^{-2} \text{mag}^{-1} \) for \( E_{B-V} = 0.13 \text{mag} \).

For SN 2014J, the gas column density is estimated to be \( \log N_H = 21.53 \pm 0.13 \text{ (see Table 3 in Ritchey et al. 2015)} \). Thus, \( N_H/E_{B-V} = 2.47 \times 10^{21} \text{cm}^{-2} \text{mag}^{-1} \) for model 1 with \( E_{B-V} = 1.37 \text{mag} \). For model 2, in which IS dust only contributes \( E_{B-V} = 0.45 \) (Foley et al. 2014), we obtain \( N_H/E_{B-V} = 7.52 \times 10^{21} \text{cm}^{-2} \text{mag}^{-1} \).

In Table 1 we summarize the parameters of four SNe Ia used for the inversion process (see also Patat et al. 2015). We note that the adopted values of \( \lambda_{\text{max}} \) and \( K \) taken from Patat et al. (2015), which were derived from the fits to observations using the Serkowski law, may not reflect underlying physics adequately. Let’s assume conservatively that these values of \( \lambda_{\text{max}} \) and \( R_V \) are reliable and we will explore the properties and grain alignment of dust in the host galaxy.

### 3.2.2. Metal Abundances in Galaxies

One important constraint is the fraction of metal elements (e.g., Si, Fe, Mg, and C) incorporated into dust. Let us now evaluate the silicate volume per H atom. Assuming that all Mg, Si, and Fe budgets (Anders & Grevesse 1989) are incorporated in the solid silicate material, then, for each Si atom, we would form a structure \( \text{Mg}_2\text{SiO}_4 \). The volume of silicate material per H atom is \( V_{\text{sil},0}/H = (\text{Si}/H)p_{\text{sil}}/p_{\text{H}} = 2.57 \times 10^{-27} \text{cm}^3/\text{H} \) for \( r_{\text{pl}} = 3.5 \text{ g cm}^{-3} \). Similarly, for graphite with \( r_{\text{pl}} = 2.2 \text{ g cm}^{-3} \), we get \( V_{\text{gra},0}/H = 2.23 \times 10^{-27} \text{cm}^3/\text{H} \) with \( C/H = 2.46 \times 10^{-4} \). The volume of the dust component of the model is evaluated by \( V_j = \int (4\pi a^3/3)da_{\text{ij}}/da \).

### 4. Monte Carlo Inversion Technique and Results

An inversion technique has frequently been used to infer the grain size distribution of dust grains in the ISM of the Milky Way (Kim et al. 1994; Larson et al. 2000; Zubko et al. 2004) and in nearby galaxies (e.g., Small Magellanic Cloud; Clayton et al. 2003). Draine & Fraisse (2009) used the Levenberg–Marquart method to infer both the grain size distribution and the alignment function of interstellar grains in the Galaxy, characterized by the typical values of \( R_V = 3.1 \) and \( \lambda_{\text{max}} = 0.55 \text{μm} \). Here we follow Hoang et al. (2013, 2014, hereafter HLM13, HLM14) using the Monte Carlo method to find the best-fit grain size distribution and the alignment function for interstellar grains in the SN Ia-hosted galaxies with anomalous extinction and polarization data.

#### 4.1. Simulation-based Inversion Technique

To study dust properties and grain alignment toward SNe Ia, we will find the best-fit grain size distribution and alignment function by fitting the observed extinction and polarization curves with the theoretical models \( A_{\text{mod}} \) and \( p_{\text{mod}} \). The observed data for the SNe Ia are calculated using Equation (1) and the CCM law, with the relevant parameters shown in Table 1. Our nonlinear least-squares fitting code uses the Monte Carlo simulation method to minimize an objective function \( \chi^2 = \chi_{\text{mod}}^2 + \chi_{\text{con}}^2 \), where \( \chi_{\text{mod}} = \chi_{\text{ext}}^2 + \chi_{\text{pol}}^2 \) describes the misfit between the model extinction and polarization and the observed data, and \( \chi_{\text{con}}^2 \) describes the model constraints, including the smoothness of \( p_{\text{mod}} \) and the monotonic variation of \( f_{\text{p}} \) (see HLM13; HLM14, for details).

The important constraint for the polarization model and the alignment function \( f(a) \) is that, for the maximum polarization
efficiency $p_{\text{max}}/A(\lambda_{\text{max}}) = 3\% \text{ mag}^{-1}$ (see Draine 2003, for a review), we expect that the conditions for grain alignment are optimal, which corresponds to the case in which the alignment of big grains can be perfect, and the magnetic field is regular and perpendicular to the LOS. Thus, we set $f(a = a_{\text{max}}) = 1$. For a given LOS with lower $p_{\text{max}}/A(\lambda_{\text{max}})$, the constraint $f(a = a_{\text{max}})$ should be adjusted such that $f(a = a_{\text{max}}) = (1/3)p_{\text{max}}/A(\lambda_{\text{max}})$. For big grains, we expect the monotonic increase of $f(a)$ versus $a$; thus, a monotonic constraint is introduced for $a > 50$ Å. For $a < 50$ Å, expecting a different alignment mechanism based on resonance paramagnetic relaxation that results in a peaky alignment function (HLM13), we do not constrain the monotonic decrease for this very small population. Other constraints include the nonsmoothness of $dn/da$ and $f(a)$ (see Draine & Allaf-Akbari 2006).

Because the extinction and polarization data in far-UV wavelengths ($\lambda < 0.25 \mu m$) toward the considered SNe Ia are unavailable, we will not attempt to invert the data for the far-UV wavelengths, which are mainly contributed by ultrasmall grains (including polycyclic aromatic hydrocarbons). Thus, we consider $\lambda = 0.25-2.5 \mu m$ and compute the extinction and polarization model given by Equations (7) and (8), respectively. We use 64 bins of grain size in the range $a = 10$ Å to 1 μm and 64 bins of the wavelength.

The fitting procedure is started with an initial size distribution $n(a)$ that best reproduces the observational data for the typical ISM (model 3 in Draine & Fraisse 2009) and is iterated until the convergence criterion is satisfied. At each iteration step, for each size bin, we generate 32 independent sample models by perturbing all model parameters $n_a, \nu_a$ using the Gibbs sampling algorithm, and we retain the best model determined by the current minimum $\chi^2$. The process is looped over all size bins, and the final minimum $\chi^2$ is obtained for which a unique best-fit model is retained. An iteration step is accomplished. The convergence criterion is based on the decrease of $\chi^2$ after one step: $\epsilon = (\chi^2(n, f) - \chi^2(n, f))/\chi^2(n, f)$. If $\epsilon \leq e_0$ with $e_0$ sufficiently small, then the convergence is said to be achieved (see HLM13; HLM14). With the value $e_0 = 10^{-3}$ adopted, the convergence is slow for some LOSs; we stop the iteration process when the variation of $\chi^2$ is relatively stable.

4.2. Inversion Results

4.2.1. Convergence and Best-fit Models

For SN 1986G and SN 2006X, we run the inversion code assuming that the entire extinction and polarization are produced by the IS dust, and we obtain a gradual reduction of $\chi^2$. For SN 2008fp and SN 2014J, we run the inversion code for both model 1 and model 2 (see Table 1). For SN 2014J (model 1), our simulations do not show the reduction of $\chi^2$ and the minimum $\chi^2$ obtained is too large (i.e., $\chi^2 \sim 10^5$), which indicates that the inversion fails to converge. For model 2, our simulations exhibit a good reduction of $\chi^2$. Detailed evolution of $\chi^2$ and $\chi_{\text{mod}}^2$ versus the iteration step for four SNe Ia is shown in Figure 2.

From the figure, it can be seen that the achieved goodness of fits is excellent for SN 1986G and SN 2014J (model 2), which have terminal $\chi_{\text{mod}}^2 \sim 0.3-0.4$. For the case with extreme $RV$, SN 2006X, the goodness of fit is poorer with $\chi_{\text{mod}}^2 \sim 3$. SN 2008fp (model 1), with both extreme $RV$ and $\lambda_{\text{max}}$, has rather slow reduction in $\chi^2$, which requires ~100 iteration steps to reach the stable value of $\chi^2$. Interestingly, SN 2008fp (model 2) shows a similar trend to model 1, but reaches higher $\chi^2$ after ~100 steps.

Figure 3 shows best-fit models to the observed extinction (left panels) and polarization curves (right panels) for SN 1986G and SN 2006X (top) and for SN 2008fp and SN 2014J (bottom).

4.2.2. Best-fit Grain Size Distribution and Alignment Function

Figure 4 shows the best-fit model parameters for our considered SNe Ia, including the grain mass distribution and alignment function. The best-fit mass distributions show the lack of large grains of $a > 0.1 \mu m$. For instance, compared to SN 1986G, SN 2006X, with a much lower value of $RV$, requires a significant increase in the mass of small silicate grains at $a \sim 0.06 \mu m$. In particular, both SN 1986G and SN 2006X have rather similar best-fit alignment functions owing to their similar $\lambda_{\text{max}}$ inferred from fitting the Serkowski law to the observation data. In addition, the alignment of small grains $a \sim 0.05-0.1 \mu m$ is significantly increased compared to the typical alignment function in the Galaxy with $\lambda_{\text{max}} \sim 0.55 \mu m$ (e.g., see HLM14), which is required to reproduce the low values of $\lambda_{\text{max}} \sim 0.35-0.45 \mu m$.

Figure 4 (bottom panels) shows the results for SN 2008fp (models 1 and 2) and SN 2014J (model 2). Compared to SN 2006X, with a similar, low value of $RV$, SN 2008fp (model 1) requires a higher mass of very small silicate grains at $a < 0.010 \mu m$ but lower mass of small silicate grains at $a \sim 0.06 \mu m$. Similarly, the mass of small graphite grains must be enhanced to compensate for the reduction of small silicate in order to reproduce the same $RV$ as in SN 2006X. Interestingly, for SN 2008fp (model 1), the alignment degree is independent of the grain size, in which small grains must be aligned as efficiently as large grains. The best-fit size distribution and alignment function obtained for SN 2014J (model 2) are reminiscent of SN 1986G owing to their similar low values of $RV$ and inferred values of $\lambda_{\text{max}}$.

5. Discussion

5.1. Dust Properties toward SNe Ia: Enhancement in the Mass of Small Grains

In this paper, we have applied our inversion technique to infer a specific model of interstellar grains in the distant galaxies probed by SNe Ia that possess anomalous observational data. To reproduce the anomalous extinction and polarization for four SNe Ia (SN 1986G, SN 2006X, SN 2008fp, and SN 2014J), our best-fit models indicate that dust grains essentially have enhanced mass at small sizes ($a < 0.1 \mu m$), whereas large grains ($a > 0.1 \mu m$) are subdominant. This is essentially in agreement with previous works (Wang et al. 2008b; Phillips et al. 2013; Patat et al. 2015).

In particular, SN 2006X, with an extreme value of $RV = 1.31$ but a low value of $\lambda_{\text{max}} \sim 0.365 \mu m$, requires the largest enhancement in the mass of small grains of size $a \sim \lambda_{\text{max}}/2\pi \sim 0.06 \mu m$ among the considered SNe Ia. This is easily understood because to reproduce the extreme value of $RV$, it requires an increase in mass of small grains, but such additional mass must be well concentrated at not very small size to reproduce a not very low value of $\lambda_{\text{max}}$. The mass fraction of graphite in this model is estimated to be $q_{\text{gra}} \sim 8\%$. 
about 3 times lower than that in the Galaxy (\(q_{\text{gra}} \sim 20\%\)), which indicates the decrease of the depletion of C into the grain. This result appears to be in agreement with the high abundance of gas phase C (about 2 times higher than for the Galaxy) reported by Cox & Patat (2014) based on the analysis of CN absorption lines from the dense cloud.

For SN 2008fp, which exhibits unusually low values of both \(R_V\) and \(\lambda_{\text{max}} = 0.148 \, \mu m\) (model 1 without CS dust), our inversion results reveal a high mass fraction of carbonaceous grains (e.g., at \(a \sim 0.04 \mu m\)) and an efficient alignment of grains of all sizes. When including Rayleigh scattering by CS dust (model 2), we derived more reasonable parameters for the extinction and polarization curves (i.e., \(R_V = 2.2\) and \(\lambda_{\text{max}} = 0.42 \mu m\)). As a result, our best-fit results do not reveal a special grain alignment function as in model 1. This model also requires a lower mass fraction of graphite, \(q_{\text{gra}} \sim 11\%\), which seems to be consistent with estimates in Cox & Patat (2014).

For SN 2014J, our inversion for model 1 is unsuccessful, i.e., we cannot reach a target \(\chi^2\) (e.g., \(\chi^2 < 10\)). The inversion for model 2 is successful and provides a good fit to the observational data. The best-fit grain size distribution is similar to that for SN 1986G, which is expected owing to their similar values of \(R_V\) and \(\lambda_{\text{max}}\). So the best-fit alignment becomes closely similar to that of SN 1986, SN 2006X, and SN 2008fp (model 2), which indicates a universal alignment of interstellar grains along the LOSs to these SNe Ia. Previous studies using only extinction fitting (Gao et al. 2015; Nozawa 2016) also found an excess of small grains toward these SNe.

Lastly, the remaining question is, why do the environments toward these SNe Ia have enhanced relative abundance of small grains?

High relative abundance of small grains may arise from several processes, including galaxy evolution, dust formation in SNe II and asymptotic giant branch (AGB) stars, and dust evolution (see Patat et al. 2015). Here we suggest that small grains may be replenished owing to cloud–cloud collisions induced by strong radiation pressure of SNe Ia.

Indeed, grains in a molecular cloud initially located closer to the explosion site are accelerated by strong SN radiation pressure to high terminal velocities, as given by \(v \approx 171 (L_{\text{bol}}/10^{43} L_{\odot})^{1/2} (r_e/100\,\text{pc})^{-1/2} a_{-5}^{-1/2} \, \text{km s}^{-1}\) (see Hoang et al. 2015), and this cloud may be ejected as well. The ejecting cloud would collide with another cloud in its vicinity (e.g., for SN 1986G and SN 2014J), which certainly results in the fragmentation of big grains. It is noted that the drifting motion of fast grains through the ambient gas results in nonthermal sputtering of the grains, which reduces the abundance of very small grains. But this process usually takes a long timescale to be important, i.e., \(\tau_{\text{gr}} \sim a_{-5} \rho_{\text{gas, gr}} m_{\text{H}} \sim 500 a_{-5} \rho/3 \, \text{g cm}^{-3}/(n_{\text{gas}}/100 \, \text{cm}^{-3}) (v_{\text{gr}}/100 \, \text{km s}^{-1}) \, \text{yr}\). Therefore, these scenarios have little impact on the time variability of extinction and polarization toward SNe that are usually carried out within several weeks after the explosions.

### 5.2. Alignment of Interstellar Dust Grains toward the SNe Ia

#### 5.2.1. SNe Ia with Low Values of \(\lambda_{\text{max}} \sim 0.3\,– \,0.45 \,\mu m\)

The polarization curves for SN 1986G and SN 2006X exhibit low values of \(\lambda_{\text{max}} \sim 0.3\,– \,0.45 \,\mu m\). For SN 2008fp and SN 2014J, when accounting for the effect of Rayleigh scattering (model 2), we found that their values of \(\lambda_{\text{max}}\) become less extreme, as small as in SN 1986G and SN 2006X. To reproduce such low values of \(\lambda_{\text{max}}\), we find that the enhancement in relative abundance of small silicate grains is sufficient, while the alignment function exhibits a normal behavior in which grains larger than \(a \sim 0.05 \,\mu m\) are efficiently aligned as in the Galaxy (see Figure 4). This normal alignment of interstellar grains is most likely possible via the radiative torque (RAT) mechanism induced by interstellar radiation fields (see Lazarian et al. 2015, for a review). It is noted that both SN 1986G and SN 2014J exploded in the disk of starburst galaxies NGC 5128 and NGC 3034, respectively, and there exist numerous clouds along the LOS. Therefore, the grain alignment in these cases would reflect the alignment properties of dust grains in the average ISM of the host galaxies.
5.2.2. SNe Ia with Extreme Values of $\lambda_{\text{max}} < 0.2$ $\mu$m: Radiative Torque Alignment by Radiation from SNe Ia

Among the SNe Ia considered, SN 2008fp is an exceptional case in which both model 1 and model 2 could reproduce the observational data. Model 1 without CS dust provides a slightly better fit (smaller $\chi^2$), but its extreme value of $\lambda_{\text{max}} = 0.15$ $\mu$m requires that small grains ($a \sim 0.01$) are aligned as efficiently as big grains. This is unusual because small grains are usually found to be weakly aligned, e.g., in the Galaxy (Kim & Martin 1995; HLM14). Therefore, it is important to understand whether such a special grain alignment is physically possible.

Over the past few years, we have witnessed significant progress in theoretical and observational studies of grain alignment, and RAT alignment has become a leading mechanism for the alignment of interstellar grains (see Andersson et al. 2015; Lazarian et al. 2015, for reviews). According to the RAT model, the alignment of irregular grains depends on a number of physical parameters, including the grain size, the radiation energy density, the mean wavelength of the radiation spectrum, the angle between the anisotropic direction of the radiation field and the magnetic field, and the local gas density and temperature (Lazarian & Hoang 2007; Hoang & Lazarian 2008, 2009). For an SN of luminosity $L_{SN}$, the radiation energy density at distance $d_{\text{pc}}$ in units of pc is given by

$$u_{\text{rad}} = \int u_0 d\lambda = \int \frac{L_{\lambda} e^{-\tau_{\lambda}}}{4\pi c d^2} d\lambda,$$

$$\simeq 1.06 \times 10^{-7} \frac{L_{\text{IR}} e^{-\tau}}{d_{\text{pc}}^2} \text{ erg cm}^{-3},$$

where $u_\lambda$ is the spectral energy density, $\tau_\lambda$ is the optical depth induced by intervening dust, $L_\lambda = L_{SN}/10^8 L_{\odot}$, and $\tau$ is defined as $e^{-\tau} = \int L_{\lambda} e^{-\tau} d\lambda/L_{SN}$.

Thus, the critical size above which grains are efficiently aligned, $a_{\text{eff}}$, is determined by the maximum angular momentum induced by RATs, which is equal to (see Lazarian & Hoang 2007; Hoang & Lazarian 2014)

$$J_{\text{max}} \approx 30 \tau_{\text{IR}}^{1/2} \lambda_{\text{IR}}^{1/2} \left( \frac{L_{\text{IR}} e^{-\tau}}{d_{\text{pc}}^2} \right) \left( \frac{20}{T_{\text{gas}}} \right),$$

$$\times \left( \frac{1.2}{\mu m} \right) \left( \frac{10^{10} L_{\text{IR}} e^{-\tau}}{d_{\text{pc}}^2} \right) \left( \frac{Q_{\gamma}^{-1}}{1 + F_{\text{IR}}} \right),$$

where $J_{\text{th}}$ is the thermal angular momentum of grains at gas temperature, $F_{\text{IR}}$ is the damping coefficient due to infrared
emission, $\xi_{\text{rad}} = \gamma_{\text{rad}}/0.1$ with $\gamma_{\text{rad}}$ the anisotropy degree of the radiation field (unity in our case), and $\lambda$ and $\overline{Q}_\lambda$ are the wavelength and RAT efficiency averaged over the entire radiation field spectrum, respectively. Here we disregard the effect of the interstellar radiation field, which is small compared to the SN radiation in the clouds close to the SN.

For interstellar grains with $a \ll \lambda$, $\overline{Q}_\lambda$ is approximately equal to (Hoang & Lazarian 2014)

$$\overline{Q}_\lambda \simeq 2 \left( \frac{\lambda}{a} \right)^{-2.7} \simeq 2.4 \times 10^{-3} \left( \frac{\lambda}{1.2 \, \mu \text{m}} \right)^{-2.7} a^{-2.7}. \quad (11)$$

Grains are expected to be efficiently aligned when spun up to suprathermal speeds, which is determined by the criteria $J_{\text{max}} \gtrsim 3J_\text{th}$ (see Hoang & Lazarian 2008). The timescale in which RATs can spin up grains to suprathermal rotation is equal to

$$\tau_{\text{spin-up}} = \frac{J_{\text{th}}}{dJ/dt} = \frac{\tau_{\text{drag}}}{J_{\text{max}}/J_{\text{th}}},$$

$$\simeq \frac{6.58 \times 10^4 a^{-1} n_\text{H}^{-1} T_2^{3/2}}{J_{\text{max}}/J_{\text{th}}} \text{yr}, \quad (12)$$

where $\tau_{\text{drag}} \simeq 6.58 \times 10^4 a^{-1} n_\text{H}^{-1} T_2^{3/2}/(1 + F_{\text{IR}})$ yr, with $n_\text{H} = n_\text{H}/10 \text{ cm}^{-3}$ being the rotational dampingtime due to gas drag.

Plugging in numerical values, we get

$$\tau_{\text{spin-up}} \simeq 0.5 \left( \frac{d_{\text{pc}}^2}{L_\lambda e^{-\tau}} \right)^{1.7} a^{-2.2} \text{ days.} \quad (13)$$

Radiation energy of SNe Ia is produced mostly by conversion of the kinetic energy of ejecta interacting with surrounding environments (i.e., shocked regions). Most of such energy is concentrated in UV–optical wavelengths, especially in early epochs after the explosion (see Brown et al. 2009). For simplicity, let us assume that the emitting region can be approximately described by a blackbody of effective temperature $T_\text{SN}$. Thus, we can estimate $\lambda = \int \lambda n_\lambda(T_\text{SN})d\lambda / \int n_\lambda(T_\text{SN})d\lambda$. This gives $\lambda = 0.35 \, \mu \text{m}$ for $T_\text{SN} = 1.5 \times 10^4 \text{K}$.

In Figure 5 we show $d_{\text{ali}}$ (left panel) and $\tau_{\text{spin-up}}$ (right panel) as functions of $d_{\text{pc}}$ for different values of $n_\text{H}$ and $L_\lambda e^{-\tau}$. The left panel shows that small grains $a_{\text{ali}} \sim 0.01 \, \mu \text{m}$ in the cloud at distances $d \sim 20 \, \text{pc}$ with the gas density $n_\text{H} \sim 250 \, \text{cm}^{-3}$ (as estimated for SN 2008fp in Cox & Patat 2014) could be aligned. For a very dense cloud $n_\text{H} \sim 10^4 \, \text{cm}^{-3}$, it must be very close at $d \sim 3 \, \text{pc}$ to give $a_{\text{ali}} \sim 0.02 \, \mu \text{m}$ for $L_\lambda e^{-\tau} < 1$. These small distances compared to the galaxy scale indicate that the clouds are close to the explosion site in order to reproduce the observed polarization.

Figure 4. Grain mass distribution (red for silicate and blue for graphite) and alignment function for the best-fit models for the considered SNe Ia. SN 2006X exhibits a substantial enhancement in the mass of small grains $a \sim 0.06 \, \mu \text{m}$ compared to SN 1986G. SN 1986G, SN 2006X, SN 2008fp (model 2), and SN 2014J (model 2) have similar alignment functions with low alignment degree of small grains of $a < 0.04 \, \mu \text{m}$. The alignment function of SN 2008fp (model 1) appears to be peculiar.
One important feature of the RAT alignment is the spin-up time, which may be longer than the observation time since the explosion. Figure 5 shows that for a cloud at distance \( d \sim 1\text{--}10\text{ pc} \) (i.e., well beyond the sublimation radius; see Hoang et al. 2015), the a \( \sim 0.03\ \mu\text{m} \) grains can be radiatively aligned on \( t_{\text{spin-up}} \sim 0.3\text{--}30\text{ days for } L_{\text{SN}} = 10^8 L_{\odot} \).

It is noted that polarimetric observations of SN 2008fp were performed on \( -2, 3, 9, \) and \( 31\text{ days relative to the maximum epoch (Cox & Patat 2014). As a result, RAT alignment by the radiation from SNe requires the cloud to be within 10 pc such that } t_{\text{obs}} > t_{\text{spin-up}} \). For SN 2014J, the observations were carried out on three epochs (January 28, February 3, and March 8, 2014), with the maximum brightness in the first week of February (Patat et al. 2015). The situation is more complicated because the LOS toward this SN contains more than 20 clouds.

One related issue is that if the RAT alignment by SN Ia radiation is at work, then why do other SNe Ia not exhibit extreme values of \( \lambda_{\text{max}} \)? The first reason may be that this cloud is located farther away than the single cloud in SN 2008fp, or the radiation from the central source is significantly reduced by the larger optical depth \( \tau \) arising from circumstellar dust (e.g., for SN 2014J) or intervening clouds.

Lastly, our discussion of RAT alignment of grains in intervening clouds above can be applied to CS dust; the only difference is that in the latter the radiation from white dwarfs (WDs) induces grain alignment. Our estimate for a typical WD with \( T_s \sim 10^5\text{ K and } R_s \sim 0.01 R_\odot \) shows that grains can be aligned within \( 10 R_s \). Nevertheless, those grains will be swept out rapidly after SN explosion (see Section 5.3) and have no impact on the polarization degree and dispersion angles through the SN explosion epochs.

### 5.2.3. Observational Signatures of RAT Alignment by SN Ia Radiation

The variability of the SN luminosity results in the variation of \( a_{\text{ali}} \) which apparently induces the variation of the polarization curves. To illustrate such an effect, we compute a number of polarization curves by varying \( a_{\text{ali}} \), where a typical grain size distribution of the Galaxy (Draine & Li 2007) is chosen. The alignment function is assumed to be \( f_a = 1 - \exp[-(a/a_{\text{ali}})^3] \), which captures our best-fit alignment functions shown in Figure 4. The obtained results are shown in Figure 6. It is shown that when \( a_{\text{ali}} \) is decreased from 0.03 to 0.001 \( \mu\text{m} \), the polarization at \( \lambda < 0.4\ \mu\text{m} \) varies substantially, whereas its variation at \( \lambda > 0.4\ \mu\text{m} \) is rather small.

The increase and decrease of the polarization at \( \lambda < 0.4\ \mu\text{m} \) before and after the maximum luminosity epoch are unique signatures of RAT alignment toward SNe. Therefore, observing the far-UV SN polarization would provide important insight into the origin of anomalous polarization and the RAT alignment mechanism. Because the IS polarization is determined by the interstellar magnetic fields, the polarization angles are stable through the different epochs of SN observations. Thus, this model of RAT alignment naturally explains the lack of variability of polarization vectors (see Patat et al. 2015; Porter et al. 2016).
5.3. Circumstellar Dust and Implications for SN Ia Progenitors

Using our inversion technique, we found that the presence of CS dust in SN 2008fp is uncertain because our inversion is successful for models both without and with CS dust. Including CS dust allows us to get dust parameters $R_f$ and $\lambda_{\text{max}}$ to be similar for four SNe Ia, and the alignment function of the IS dust toward these SNe Ia appears to be universal. However, it has been argued that CS dust is unlikely to be important for SN 2008fp owing to the lack of variability in the polarization angles (Patat et al. 2015; Maeda et al. 2016), as well as the lack of variability of extragalactic absorption line profiles (see Cox & Patat 2014).

The existence of CS dust in SN 2014J is still strongly debated. Some groups claim that the extinction to SN 2014J is dominated by interstellar dust (Brown et al. 2015; Patat et al. 2015), whereas others (Foley et al. 2014) suggest that the CS dust may be important. Our model with CS dust can be successfully obtained, indicating that the CS dust is likely important. This is in agreement with a recent analysis of the M82 region before SN 2014J by Hutton et al. (2015) that supports the contribution of both CS dust and IS dust for low $R_f$.

Patat et al. (2015) argued that the presence of CS dust in SN 2014J may not be ruled out, although the lack of variability in the polarization degrees and polarization angles is difficult to reconcile. The authors suggested that if scattering is a dominant source of observed polarization, then the geometry of CS dust clouds has to be such that the resulting polarization angle, by coincidence, is aligned with that of the local magnetic field.

A possible source that can explain the invariance of the polarization is a WD containing an accretion disk within its magnetosphere (private communication with B.-G. Andersson). Small dust grains in the disk then undergo Rayleigh scattering with the polarization perpendicular to the disk plane. If the accretion disk is parallel to the Galactic plane, the polarization by scattering is parallel to the interstellar polarization, successfully explaining the invariability of the polarization angles. However, dust grains in the accretion disk and magnetosphere would likely be swept away by SN ejecta shortly after the explosion, which is a serious challenge for this toy model.

Indeed, the WD magnetosphere is characterized by the Alfvén radius at which the magnetic energy is balanced with the gas thermal energy, which is given by

$$R_A \sim \left(3B_0^2 R_\star^6 / 2M \sqrt{GM_*} \right)^{2/7},$$

$$\simeq 1.2 R_\star B_0 (kG)^{1/7} (M/10^6 \text{ g s}^{-1} \text{y}^{-2})^{-1/7} \times (R_f/0.01 R_\star)^{1/12} (M_*/0.6 M_\odot)^{-1/7},$$

where $M_\star$ is the accretion rate and $B_\star$ is the magnetic field (see Metzger et al. 2012). For typical parameters $M \sim 10^{55} - 10^{57} \text{ g s}^{-1}$ and $B_\star \sim 1 - 100 \text{ kG}$, it yields $R_A \sim 0.3 - 62 R_\star \times (R_f/0.01 R_\star)^{1/2} (M_*/0.6 M_\odot)^{-1/7}$.

It can be seen that dust grains within the magnetosphere would be swept away after $t \approx 100 R_\star / \nu_f \approx 2.1 (\nu_f / 0.03 \text{ c})^{-1} \text{ hr}$, where the ejecta velocity during the free-expansion period is $\nu_f \approx 10^4 \text{ km s}^{-1}$. As a result, observations at hours after the SN explosion would not see any signatures of such dust.

5.4. Magnetic Alignment and Implication for Magnetic Fields in Host Galaxies

It is worth mentioning an alternative paramagnetic alignment mechanism that is proposed by Davis & Greenstein (1951) to explain starlight polarization. However, paramagnetic alignment of thermally rotating small grains is found to be inefficient (Lazarian 1997; Hoang et al. 2014). Without suprathermal rotation, even grains with superparamagnetic inclusions are far from being efficiently aligned (Roberge & Lazarian 1999; Hoang & Lazarian 2016). The joint action of RATs and superparamagnetic inclusions would result in the perfect alignment of sufficiently large grains (Lazarian & Hoang 2008).

Hoang et al. (2014) found that increasing the strength of magnetic fields can produce enhancement of alignment of small grains, which partly results in the low values of $\lambda_{\text{max}}$ and accounts for the polarization excess in the far-UV ($\lambda < 0.2 \mu \text{m}$). Considering the environment conditions of the four SNe Ia of interest, we see that SN 1986G and SN 2014J belong to the starburst galaxies, which usually exhibit stronger magnetic fields than normal galaxies (Thompson et al. 2006). Thus, the low values of $\lambda_{\text{max}}$ perhaps arise from the high magnetic fields as predicted by HLM14. If this is the case, far-UV polarimetric observations using SNe Ia would provide valuable constraints on the interstellar magnetic fields of external galaxies.

The interstellar magnetic field along the LOSs toward SNe Ia likely undergoes wandering due to interstellar turbulence. In our inversion technique, the effect of the magnetic field wandering is incorporated into the alignment function $f = 8R \cos^2 \beta$, where $\beta$ is the angle between the mean regular field and the plane of the sky, and $\Phi$ describes the average fluctuations of the local field with the LOS. The maximum value of $f$ is constrained such that $P_{\text{max}}/A(\lambda_{\text{max}}) = 3\% / \text{mag}$ corresponds to $f_{\text{max}} = 1$.

Lastly, we note that, for our modeling, we have not fitted to real observational data but to the analytical fits (CCM and Serkowski laws) of the observations. The reason for that is that we attempt to infer dust properties and grain alignment for the wide range of grain size, from ultrasmall to large grains. Due to the lack of UV observations, analytical fits are useful to extrapolate for the UV data from available data in optical and near-IR. As a result, the major caveat of our modeling is the uncertainty in the inferred values $R_f$ and $\lambda_{\text{max}}$ due to the lack of UV data. However, our modeling will be updated easily when future UV observations are available.

6. Summary

In the present paper, we have studied the properties and alignment of interstellar dust grains in external galaxies through four SNe Ia. The main findings are summarized as follows.

1. Using an inversion technique, we have obtained the best-fit grain size distribution and alignment function that simultaneously reproduce the observed extinction and polarization of four SNe Ia (SN 1986G, SN 2006X, SN 2008fp, and SN 2014J) with the anomalous values of $R_f$ and $\lambda_{\text{max}}$.

2. The best-fit grain size distributions reveal an enhancement in the mass of small silicate grains with a peak around $a \sim 0.06 \mu \text{m}$. It is suggested that the enhanced
relative abundance of small grains may be produced by cloud–cloud collisions induced by SN radiation pressure.

3. For model 1 of SN 2008fp (without CS dust), we find that to reproduce the observational data, increasing the relative abundance of small grains is insufficient. Instead, the alignment of small grains ($a \sim 0.01 \mu m$) must be as efficient as big grains. Including the effect of CS dust, the alignment function becomes more reasonable, similar to that for SN 1986G and SN 2006X. The fit is, however, not improved, and the existence of CS dust is still uncertain.

4. We have suggested a model of grain alignment based on radiative torques induced by direct, strong radiation from SNe, which can adequately explain the efficient alignment of small grains for model 1 of SN 2008fp. Far-UV polarimetric observations would be useful to differentiate the effect of IS dust and CS dust based on its polarization spectra.

5. The existence of CS dust around SN 2014J is suggested by our successful inversion when both CS dust and IS dust must be accounted for in the observed extinction and polarization.

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References

Amanullah, R., Johansson, J., Goobar, A., et al. 2015, MNRAS, 453, 3300
Anders, E., & Grevesse, N. 1989, GeCoA, 53, 197
Anderson, C. M., Weitenbeck, A. J., Code, A. D., et al. 1996, AJ, 112, 2726
Andersson, B.-G., Lazarian, A., & Vaillancourt, J. E. 2015, ARA&A, 53, 501
Andersson, B.-G., Pirola, V., De Buizer, J., et al. 2013, ApJ, 775, 84
Anderson, B.-G., & Potter, S. B. 2007, ApJ, 665, 369
Brown, P. J., Holland, S. T., Immer, S., et al. 2009, AJ, 137, 4517
Brown, P. J., Smirnova, M. T., Wang, L., et al. 2015, ApJ, 805, 74
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chiar, J. E., Adamson, A. J., Whittet, D. C. B., et al. 2006, ApJ, 651, 268
Clayton, G. C., Wolff, M. J., Sofia, U. J., Gordon, K. D., & Miret, K. A. 2003, ApJ, 588, 871
Cox, N. L. J., & Patat, F. 2008, A&A, 485, L9
Cox, N. L. J., & Patat, F. 2014, A&A, 565, A61
Cristiani, S., Cappellaro, E., Turatto, M., et al. 1992, A&A, 259, 63
Davis, L. J., & Greenstein, J. L. 1951, ApJ, 114, 206
D'Odorico, S., Di Serego Alighieri, S., Pettini, M., et al. 1989, A&A, 215, 21
Draine, B. T. 2003, ARA&A, 41, 241
Draine, B. T., & Allaf-Akbari, K. 2006, ApJ, 652, 1318
Draine, B. T., Dale, D. A., Bendo, G., et al. 2007, ApJ, 663, 866
Draine, B. T., & Fraisse, A. A. 2009, ApJ, 696, 1
Draine, B. T., & Li, A. 2007, ApJ, 657, 810
Foley, R. J., Fox, O. D., McCully, C., et al. 2014, MNRAS, 443, 2887
Fossey, S. J., Cooke, B., Pollack, G., Wilde, M., & Wright, T. 2014, CBET, 3792, 1
Gao, J., Jiang, B. W., Li, A., Li, J., & Wang, X. 2015, ApJ, 807, L26
Goobar, A. 2008, ApJL, 686, L103
Hoang, T., & Lazarian, A. 2008, MNRAS, 388, 117
Hoang, T., & Lazarian, A. 2009, ApJ, 697, 1316
Hoang, T., & Lazarian, A. 2014, MNRAS, 438, 680
Hoang, T., & Lazarian, A. 2016, ApJ, 831, 159
Hoang, T., Lazarian, A., & Martin, P. G. 2013, ApJ, 779, 152
Hoang, T., Lazarian, A., & Martin, P. G. 2014, ApJ, 790, 6
Hoang, T., Lazarian, A., & Schlickeiser, R. 2015, ApJ, 806, 255
Hough, J. H., Bailey, J. A., Rouse, M. F., & Whittet, D. C. B. 1987, MNRAS, 227, 1
Hutton, S., Ferreras, I., & Yershov, V. 2015, MNRAS, 452, 1412
Kawabata, K. S., Akitaya, H., Yamanaka, M., et al. 2014, ApJL, 795, L4
Kim, S.-H., & Martin, P. G. 1995, ApJ, 444, 293
Kim, S.-H., Martin, P. G., & Hendry, P. D. 1994, ApJ, 422, 164
Larson, K. A., Larson, K. A., Wolff, M. J., et al. 2000, ApJ, 532, 1021
Lazarian, A. 1997, MNRAS, 288, 609
Lazarian, A., Andersson, B.-G., & Hoang, T. 2015, in Polarimetry of Stars and Planetary Systems, ed. L. Kolokolova, J. Hough, & A.-C. Levasseur-Regourd (New York: Cambridge Univ. Press), 81
Lazarian, A., & Hoang, T. 2007, MNRAS, 378, 910
Lazarian, A., & Hoang, T. 2008, ApJL, 676, L25
Maeda, K., Tajitsu, A., Kawabata, K. S., et al. 2016, ApJ, 816, 57
Metzger, B. D., Rafikov, R. R., & Bochkarev, K. V. 2012, MNRAS, 423, 505
Nobili, S., & Goobar, A. 2008, A&A, 487, 19
Nozawa, T. 2016, P&SS, 133, 36
Parkin, T. J., Wilson, C. D., Foyle, K., et al. 2012, MNRAS, 422, 2291
Patat, F., Baade, D., Höflich, P., et al. 2009, A&A, 508, 229
Patat, F., Taubenberger, S., Cox, N. L. J., et al. 2015, A&A, 577, A53
Phillips, M. M., Simon, J. D., Morrell, N., et al. 2013, ApJ, 779, 38
Porter, A. L., Leising, M. D., Williams, G. G., et al. 2016, ApJ, 828, 24
Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, ApJ, 116, 1009
Ritchey, A. M., Welty, D. E., Dahlstrom, J. A., & York, D. G. 2015, ApJ, 799, 197
Roberge, W. G., & Lazarian, A. 1999, MNRAS, 305, 615
Serkowski, K., Mathewson, D. S., & Ford, V. L. 1975, ApJ, 196, 261
Thompson, T. A., Quataert, E., Waxman, E., Murray, N., & Martin, C. L. 2006, ApJ, 645, 186
Welty, D. E., & Wheeler, J. C. 2008, A&A, 46, 433
Wang, X., Li, W., Filippenko, A. V., et al. 2008a, ApJ, 675, 626
Wang, X., Li, W., Filippenko, A. V., et al. 2008b, ApJ, 677, 1060
Wang, X., Wang, L., Filippenko, A. V., et al. 2012, ApJ, 749, 126
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296
Welty, D. E., Ritchey, A. M., Dahlstrom, J. A., & York, D. G. 2015, ApJ, 792, 106
Whittet, D. C. B., Martin, P. G., Hough, J. H., et al. 1992, ApJ, 386, 562
Wilking, B. A., Lebofsky, M. J., Kemp, J. C., Martin, P. G., & Rieke, G. H. 1980, ApJ, 235, 905
Zubko, V., Dwek, E., & Arendt, R. G. 2004, ApJS, 152, 211