Variation of Dust Properties with Cosmic Time Implied by Radiative Torque Disruption

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Abstract

Dust properties within a galaxy are known to change from the diffuse medium to dense clouds due to increased local gas density. However, the question of whether dust properties change with redshift remains elusive. In this paper, using the fact that the mean radiation intensity of the interstellar medium (ISM) of star-forming galaxies increases with redshift, we show that dust properties should change due to increasing efficiency of rotational disruption by radiative torques, an effect named radiative torque disruption (RATD). We first show that because of RATD, the size distribution of interstellar dust varies with redshift, for instance, dust grains become smaller at higher $z$. We model the extinction curves and find that the curve becomes steeper with increasing redshift. The ratio of total-to-selective extinction, $R_V$, decreases with redshift and achieves low values of $R_V \sim 1.5$--2.5 for grains having a composite structure. We also find that dust properties change with the local gas density because of RATD, but the change is dominated by the radiation field for the diffuse ISM. The low values of $R_V$ implied by RATD of interstellar dust could reproduce anomalous dust extinction observed toward supernovae Ia and Small Magellanic Cloud-like extinction curves with a steep far-UV rise toward high-$z$ galaxies. Fluctuations in $R_V$ due to interstellar turbulence and varying radiation intensity may resolve the tension in measurements of the Hubble constant using supernovae Ia. We finally discuss the implications of evolving dust properties for high-$z$ astrophysics.

Unified Astronomy Thesaurus concepts: Interstellar dust (836); Interstellar dust extinction (837); Interstellar medium (847); Type Ia supernovae (1728); High-redshift galaxies (734)

1. Introduction

Interstellar dust is an essential component of the interstellar medium (ISM) and plays critical roles in astrophysics, including gas heating, star and planet formation, and grain-surface chemistry (see Mathis 1990 and Draine 2003 for reviews). Dust extinction and emission are key for extragalactic astrophysics, including measurements of star formation efficiency and understanding cosmic evolution (Calzetti 2001; see Salim & Narayan 2020 for a review). Accurate measurements of star formation rate (SFR) depend crucially on dust properties, including grain size distribution, shape, and composition. Among the different dust properties, the grain size distribution is the most important parameter that determines emission, extinction, and polarization of dust.

Following the popular paradigm of dust evolution, stardust grains form in the dense outflows of evolved stars and in the dense ejecta of core-collapse supernovae, which dominantly produce large grains (Nozawa et al. 2003). Such large grains are then fragmented into small grains by shattering in shocks when they are released into the diffuse ISM (Jones et al. 1994). Subsequently, interstellar dust is reprocessed in the ISM by growth (gas accretion and coagulation) and destruction processes, including sublimation, sputtering, and shattering in shocks. Thus, the size distribution of interstellar dust is determined by the balance between growth and destruction processes in the ISM. On the other hand, dust properties are expected to change from the diffuse ISM (with a gas density lower than 100 cm$^{-3}$) to dense molecular clouds (density higher than 100 cm$^{-3}$) due to gas accretion and grain coagulation (Zhukovska et al. 2016). This process is mostly determined by the gas density, which controls gas–grain and grain–grain collision rates. This dust evolution cycle inevitably changes the internal structure of grains from a presumably compact structure for stardust to a composite structure for interstellar dust (Mathis 1990; Draine & Hensley 2020). Therefore, dust properties in the ISM of a galaxy are expected to change. The question now is, when the same gas density as in the ISM is assumed, whether and how dust properties change with cosmic time (i.e., redshift).

Recently, Hoang et al. (2019) introduced a new physical mechanism of dust destruction that changes the size distribution of interstellar grains through radiative torques (RATs), which was termed radiative torque disruption (RATD). The basic idea of the RATD mechanism is that dust grains of irregular shape, when irradiated by anisotropic radiation field, experience RATs (Dolginov & Mitrofanov 1976; Draine & Weingartner 1996; Lazarian & Hoang 2007) and can be spun-up to extremely fast rotation (Draine & Weingartner 1996; Hoang & Lazarian 2009). Resulting centrifugal stress can exceed the maximum tensile strength of grain material, resulting in the disruption of the grain into fragments. Previously, Silsbee & Draine (2016) noted that interplanetary grains of fluffy structure could be disrupted by RATs induced by solar radiation. Since rotational disruption acts to break loose bonds between the grain constituents, unlike breaking strong chemical bonds between atoms in thermal sublimation, RATD can work with the average interstellar radiation field (ISRF; see Hoang 2020 for a review). The RATD mechanism introduces a new environment parameter for dust evolution, namely the local radiation intensity, and is found to be the most efficient mechanism that constrains the upper limit of the size distribution (Hoang 2019). Simulations of grain evolution with cosmic time in Hirashita & Hoang (2020) show that RATD is indeed the key factor determining the upper cutoff of the size distribution. The efficiency of RATD depends on the local conditions, including gas density and radiation field, grain properties (internal structure, size, and shape; Hoang 2019), and grain alignment (Lazarian & Hoang 2020). Therefore, if the density and radiation strength vary with redshift, the local
environment changes, and dust properties should change accordingly.

It is well known that the SFR increases with redshift (see Bethermin et al. 2015 and references therein). Since the mean intensity of the ISM of galaxies is governed by star formation activity, it is expected to increase with $z$. Numerous observations reveal the increase in dust temperature with redshift (Ouchi et al. 1999; Magdis et al. 2012; Bethermin et al. 2015; Faisst et al. 2017; Ferrara et al. 2017; Hirashita et al. 2017; Somm mogvo et al. 2020). Theoretical studies (del P. Lagos et al. 2012; Cowley et al. 2017; Imara et al. 2018) and cosmological simulations (Narayanan et al. 2018) imply the increase in mean radiation intensity with redshift. Hwang et al. (2010) also found an increase in $T_H$ with redshift using Herschel. Other studies of star-forming galaxies also report an increase in mean radiation intensity with redshift (Magdis et al. 2012; Lim et al. 2020). Thus, the ISRF is stronger in higher-$z$ galaxies than in the Galaxy. As a result, interstellar grains experience stronger RATs and rotational disruption is more efficient, resulting in smaller grains with increasing $z$. We quantify this effect using the established relationship of the mean radiation intensity with $z$ and explore its observational consequences.

The structure of the present paper is as follows. In Section 2 we describe the ISRF of galaxies at different redshift inferred from observations that we used for our study. In Section 3 we briefly review the basic features of RATs and RATD mechanism, and derive the critical grain size for rotational disruption. In Section 4 we present numerical results for the disruption size and calculate resulting extinction curves using the size distribution constrained by RATD for different redshift and local gas density. In Section 5 we discuss the implications of our results for understanding anomalous dust properties observed toward SNe Ia and high-$z$ astrophysics. A summary of our main findings is given in Section 6.

2. ISRF of Galaxies

Let $u_0$ be the spectral energy density (SED) of a radiation field at wavelength $\lambda$. The energy density of the radiation field is then $u_{rad} = \int_0^\infty u_0 d\lambda$. To describe the strength of a radiation field, we define $U = u_{rad}/u_{ISRF}$, with $u_{ISRF} = 8.64 \times 10^{-13}$ erg cm$^{-3}$ being the energy density of the average ISRF in the solar neighborhood as given by Mathis et al. (1983). Thus, the typical value for the ISRF in the solar neighborhood is $U = 1$

For star-forming galaxies, Bethermin et al. (2015) derived the best fit for the increase in mean radiation intensity with redshift from $z = 0–4$ as

$$U = U_0(1 + z)^{\alpha_z}$$

where $U_0 = 3 \pm 1.1$ is the mean intensity at $z=0$ and $\alpha_z = 1.8 \pm 0.4$ is the power-law index (Magdis et al. 2017; Schreiber et al. 2018).

A recent analysis from Bouwens et al. (2020) obtained a best fit to observational data for the dust temperature as

$$T_d = (34.6 \pm 0.3) + (3.94 \pm 0.26)(z - 2) \text{ K},$$

for $z \sim 0–10$, which corresponds to the increase in mean radiation intensity of $U = (T_d/18.2) \text{ K}^{5.57}$ (Schreiber et al. 2018).

In the following, we use Equation (1) for $z < 4$ and Equation (2) for $z > 4$.

3. Review of Radiative Torque Disruption

3.1. RATs of Irregular Grains

Dust grains of irregular shape irradiated by an anisotropic radiation experience RAT. The magnitude of RAT is defined as

$$\Gamma \lambda = \pi a^2 \gamma u_0 \left(\frac{\lambda}{2\pi}\right) Q_{\Gamma},$$

where $\gamma$ is the anisotropy degree of the radiation field, $Q_{\Gamma}$ is the RAT efficiency, and $a$ is the effective size of the grain, which is defined as the radius of the sphere with the same volume as the irregular grain (Draine & Weingartner 1996; Lazarian & Hoang 2007).

The magnitude of the RAT efficiency, $Q_{\Gamma}$, can be approximated by a power law (Hoang & Lazarian 2008),

$$Q_{\Gamma} \approx 0.4 \left(\frac{\lambda}{1.8a}\right)^{0},$$

where $\eta = 0$ for $\lambda \lesssim 1.8a$ and $\eta = -3$ for $\lambda > 1.8a$.

Numerical calculations of RATs for several shapes of different optical constants in Lazarian & Hoang (2007) find a slight difference in RATs among the realization. An extensive study for a large number of irregular shapes by Herranen et al. (2019) shows little difference in RATs for silicate, carbonaceous, and iron compositions. Moreover, the analytical formula (Equation (4)) also agrees well with their numerical calculations. Therefore, one can use Equation (4) for the different grain compositions and grain shapes, and the difference is on the order of unity.

Let $\lambda = \int_0^\infty \lambda u_0 d\lambda / u_{rad}$ be the mean wavelength of the radiation field. For the spectrum of the ISRF in our galaxy, $\lambda = 1.2 \mu\text{m}$ (Hoang et al. 2020). We assume that the spectrum of the ISRF of galaxies is similar to the Galaxy, so that the value of $\lambda$ remains the same with redshift. In reality, $\lambda$ is expected to be smaller for higher $z$ because of the bluer radiation that is emitted by more massive stars.

The average RAT efficiency over the spectrum is defined as

$$Q_{\Gamma} = \frac{\int_0^\lambda \lambda Q_{\Gamma} u_0 d\lambda}{\int_0^\lambda \lambda u_0 d\lambda},$$

where the integrals are taken over the entire radiation spectrum.

For interstellar grains with $a \lesssim \lambda/1.8$, $Q_{\Gamma}$ can be approximated to (Hoang & Lazarian 2014)

$$Q_{\Gamma} \approx 2 \left(\frac{\lambda}{a}\right)^{-2.7} \approx 2.6 \times 10^{-2} \left(\frac{\lambda}{0.5 \mu\text{m}}\right)^{-2.7} a^{-.5},$$

where $a_s = a/(10^{-5} \text{cm})$, and $Q_{\Gamma} \sim 0.4$ for $a > \lambda/1.8$. Hoang et al. (2020) used rigorous mathematical derivations for the mean RAT and found that this scaling is a good fit to numerical calculations for the ISRF.

Therefore, the average RAT can be given by

$$\Gamma_{\text{RAT}} = \pi a^2 \gamma u_{rad} \left(\frac{\lambda}{2\pi}\right) Q_{\Gamma}$$

$$\approx 5.8 \times 10^{-29} a_s^{4.7} \gamma U \lambda_{0.5}^{-1.7} \text{ erg},$$

for $a \lesssim \lambda/1.8$, and

$$\Gamma_{\text{RAT}} \approx 8.6 \times 10^{-28} a_s^{0.5} \gamma U \lambda_{0.5} \text{ erg},$$

(7)
for $a > \tilde{\lambda}/1.8$, where the mean wavelength is normalized over the optical wavelength, $\lambda_{0.5} = \tilde{\lambda}/0.5 \mu m$.

The well-known damping process for a rotating grain is a sticking collision with gas species (atoms and molecules), followed by their thermal evaporation. Thus, for a gas with He of 10% abundance, the characteristic damping time is

$$\tau_{\text{gas}} = \frac{3}{4\sqrt{12}} \frac{I}{n_\text{H} m_\text{H} \nu_\text{th} a^4} \approx 8.74 \times 10^4 \sigma \bar{\rho} \left( \frac{30 \text{ cm}^{-3}}{n_\text{H}} \right) \left( \frac{100 \text{ K}}{T_{\text{gas}}} \right)^{1/2} \text{yr},$$

where $I = 8\pi/\rho d^2/15$ is the grain inertia moment of spherical grains, and $\nu_\text{th} = (2k_b T_{\text{gas}}/m_\text{H})^{1/2}$ is the thermal velocity of a gas atom of mass $m_\text{H}$ in a plasma with temperature $T_{\text{gas}}$ and density $n_\text{H}$ (Draine & Weingartner 1996; Hoang & Lazarian 2009). The gas damping time is estimated for spherical grains, and we disregard the factor of unity due to grain shape.

Infrared (IR) photons emitted by the grain carry away part of the grain’s angular momentum, resulting in the damping of the grain rotation. For strong radiation fields or not very small sizes, grains can achieve equilibrium temperature, such that the IR damping coefficient (see Draine & Lazarian 1998) can be calculated as

$$F_{\text{IR}} \approx \left( \frac{0.4U^{2/3}}{a^{-5}} \right) \left( \frac{30 \text{ cm}^{-3}}{n_\text{H}} \right) \left( \frac{100 \text{ K}}{T_{\text{gas}}} \right)^{1/2}.$$  \hspace{1cm} \text{(10)}$$

Other rotational damping processes include plasma drag, ion collisions, and electric dipole emission. These processes are mostly important for polycyclic aromatic hydrocarbons and very small grains of radius $a < 0.01 \mu m$ (Draine & Lazarian 1998; Hoang et al. 2010; Hoang et al. 2011). Thus, the total rotational damping rate by gas collisions and IR emission can be written as

$$\tau_{\text{damp}}^{-1} = \tau_{\text{gas}}^{-1} (1 + F_{\text{IR}}).$$

For strong radiation fields of $U \gg 1$ and not very dense gas, one has $F_{\text{IR}} \gg 1$. Therefore, $\tau_{\text{damp}} \approx \tau_{\text{gas}}/F_{\text{IR}} \approx a^{-5} U^{2/3}$, which does not depend on the gas properties. In this case, the only damping process is caused by IR emission.

For the radiation sources with stable luminosity considered in this paper, RAT, $\Gamma_{\text{RAT}}$, is constant, and the grain velocity increases steadily over time. The equilibrium rotation can be achieved at (see Lazarian & Hoang 2007; Hoang & Lazarian 2009; Hoang & Lazarian 2014)

$$\omega_{\text{RAT}} = \frac{\Gamma_{\text{RAT}} \tau_{\text{damp}}}{I}. \hspace{1cm} \text{(12)}$$

The rotation rate by RATs is given by

$$\omega_{\text{RAT}} = \frac{5a^{0.7} \gamma_{\text{uf}} \bar{\lambda}^{-1.7} \left( 1 + F_{\text{IR}} \right)}{8n_\text{H} \sqrt{2\pi m_\text{H} k_b T_{\text{gas}}} \left( 1 + F_{\text{IR}} \right)} \approx 9.22 \times 10^7 \sigma \left( \frac{0.7 \bar{\lambda}_{a0.5}^{-1.7}}{a^{-5}} \right) \times \left( \frac{\gamma_{\text{uf}} U}{n_\text{H} T_{\text{gas}}^{1/2}} \right) \frac{1}{1 + F_{\text{IR}}} \text{rad s}^{-1},$$

for grains with $a \lesssim \tilde{\lambda}/1.8$, and

$$\omega_{\text{RAT}} = \frac{a^2 \gamma_{\text{uf}} \bar{\lambda} \left( 1 + F_{\text{IR}} \right)}{4n_\text{H} \sqrt{2\pi m_\text{H} k_b T_{\text{gas}}} \left( 1 + F_{\text{IR}} \right)} \approx 1.42 \times 10^7 \sigma a^{-3} \bar{\lambda}_{a0.5} \times \left( \frac{\gamma_{\text{uf}} U}{n_\text{H} T_{\text{gas}}^{1/2}} \right) \frac{1}{1 + F_{\text{IR}}} \text{rad s}^{-1},$$

for grains with $a > \tilde{\lambda}/1.8$.

Above, $n_\text{H} = n_{\text{H}}/(10^3 \text{ cm}^{-3})$, $T_{\text{gas}} = T_{\text{gas}}/100 \text{ K}$, $\gamma_{-1} = \gamma/0.1$ is the anisotropy of radiation field relative to the typical anisotropy of the diffuse ISRF. The radiation anisotropy degree also varies with the location, between $\gamma \sim 0.1$ for the diffuse ISM (Draine & Weingartner 1997) to $\gamma \sim 0.7$ for molecular clouds (Bethell et al. 2007), and $\gamma = 1$ for grains close to a star. For our study here for the diffuse ISM, we adopt the typical value of $\gamma = 0.1$. The mean wavelength is fixed to $\bar{\lambda} = 1.2 \mu m$, although it may decrease with redshift for a harder radiation field.

### 3.2. Maximum Grain Size Constrained by RATD

A spherical dust grain of radius $a$ rotating at velocity $\omega$ develops an average tensile stress due to centrifugal force that scales as (see Hoang et al. 2019)

$$S = \frac{\rho a^2 \omega^2}{4}. \hspace{1cm} \text{(15)}$$

When the rotation rate is sufficiently high such that the tensile stress exceeds the maximum limit, namely tensile strength $S_{\text{max}}$, the grain is disrupted. The critical rotational velocity is given by $S = S_{\text{max}}$

$$\omega_{\text{disr}} = \frac{2}{a} \left( \frac{S_{\text{max}}}{\rho} \right)^{1/2} \approx \frac{3.65 \times 10^8}{a^{-5}} S_{\text{max},7}^{1/2} \rho^{-1/2} \text{rad s}^{-1},$$

where $S_{\text{max},7} = S_{\text{max}}/10^7 \text{ erg cm}^{-3}$ (Hoang et al. 2019).

The tensile strength of interstellar dust depends on grain structure (compact versus composite versus core-mantle), which is uncertain (Mathis 1990). Compact grains should have large tensile strength of $S_{\text{max}} \gtrsim 10^9 \text{ erg cm}^{-3}$, whereas composite or fluffy grains have much lower tensile strength (Hoang 2019). Large grains (radius $a > 0.1 \mu m$) are expected to have composite structure as a result of the coagulation process in molecular clouds or in the ISM. Numerical simulations for porous grain aggregates from Tatsuuma et al. (2019) find that the tensile strength decreases with increasing monomer radius and can be fit with an analytical formula (see Kimura et al. 2020 for more details),

$$S_{\text{max}} \approx 9.51 \times 10^7 \left( \frac{a_{\text{m}}}{0.1 \mu m} \right)^{1.8} \frac{\gamma_{\text{uf}}}{0.1} \frac{\phi}{\phi_{0.1}} \text{ erg cm}^{-3},$$

where $\gamma_{\text{uf}}$ is the surface energy per unit area of the material, $r_0$ is the monomer radius, and $\phi$ is the volume filling factor of monomers. For large grains ($a > 0.1 \mu m$) made of monomers
of radius $r_0 = 0.1 \, \mu m$ and $\phi = 0.1$, Equation (17) implies $S_{\text{max}} \approx 10^5 \, \text{erg cm}^{-3}$.

Throughout this paper, we assume that large grains have a composite structure, as expected from the grain evolution model in the ISM (Mathis 1990) and adopt $r_0 = 0.1 \, \mu m$, yielding the typical tensile strength of $S_{\text{max}} = 10^5 \, \text{erg cm}^{-3}$. We also explore the possibilities that grains are made of smaller monomers ($r_0 < 0.1 \, \mu m$) or have core-mantle and compact structures with a larger tensile strength of $S_{\text{max}} = 10^5 - 10^6 \, \text{erg cm}^{-3}$.

For an arbitrary radiation field and $a \leq \bar{X}/1.8$, one obtains

$$a_{\text{disr}} \simeq \left( \frac{16n_H \sqrt{2\pi m_H k T_{\text{gas}}}}{\gamma_{\text{rad}} \bar{X}_{1.7}} \right)^{1/1.7} (1 + F_{\text{IR}})^{1/1.7} \left( \frac{S_{\text{max}}}{\rho} \right)^{1/3.4}$$

$$\simeq 0.22 \bar{X}_{0.5} S_{\text{max},7}^{3/4} (1 + F_{\text{IR}})^{1/1.7} \left( \frac{n T_{1/2}}{\gamma_{-1}} \right)^{1/1.7} (1 + z)^{-0.1/1.7} \mu m,$$

which depends only on the local gas density and temperature. The disruption size is the function of two parameters: the gas density $n_H$, and the radiation strength.

Using the relationship between $U$ and redshift (Equation (1)), one obtains

$$a_{\text{disr}} \simeq 0.22 \bar{X}_{0.5} S_{\text{max},7}^{3/4} (1 + F_{\text{IR}})^{1/1.7}$$

$$\times \left( \frac{n T_{1/2}}{\gamma_{-1}} \right)^{1/1.7} (1 + z)^{-0.1/1.7} \mu m,$$

where $\alpha_z \approx 1.8$. This equation implies the inverse decrease of the disruption size with redshift as $(1 + z)^{-0.1/1.7} \sim 1/(1 + z)$.

Because the rotation rate decreases for $a > a_{\text{trans}}$ (see Equation (14)), there exist a maximum size, $a_{\text{disr,max}}$, of grains that can still be disrupted by centrifugal stress (Hoang & Tram 2020). Setting $\omega_{\text{disr}} = \omega_{\text{RAT}}$ using Equation (14) yields

$$a_{\text{disr,max}} = \frac{\gamma_{\text{rad}} \bar{X}_{1.7}}{16n_H \sqrt{2\pi m_H k T_{\text{gas}}}} \left( \frac{S_{\text{max}}}{\rho} \right)^{-1/2}$$

$$\approx 0.39 \left( \frac{\gamma_{-1}}{n T_{1/2}} \right)^{1/1.7} \bar{X}_{0.5} \rho^{1/2} S_{\text{max},7}^{1/1.7}$$

$$\times (1 + F_{\text{IR}})^{-1} \mu m,$$

which implies $a_{\text{disr,max}} \approx 3.9 \, \mu m$ for $S_{\text{max}} = 10^5 \, \text{erg cm}^{-3}$ with $U = 1$.

For strong radiation fields or low density such as $F_{\text{IR}} \propto U/n_H > 1$, IR damping dominates. The disruption size then becomes independent of gas density,

$$a_{\text{disr}} \approx 2.4 \left( \frac{\bar{X}_{1.7}}{\gamma_{-1}^{1/2}} \right)^{1/2} \left( \frac{S_{\text{max}}}{\rho} \right)^{1/5.4} \mu m$$

$$\approx 0.18 \gamma_{-1}^{1/1.7} U^{-1/8.1} \bar{X}_{0.5}^{1.7/2} (S_{\text{max},7}/\rho)^{1/5.4} \mu m,$$

which corresponds to

$$a_{\text{disr}} \approx 0.16 \gamma_{-1}^{1/2.7} (1 + z)^{-0.1/8.1} \bar{X}_{0.5}^{1.7/2.7}$$

$$\times (S_{\text{max},7}/\rho)^{1/5.4} \mu m,$$

for $a_{\text{disr}} \ll \bar{X}/1.8$.

In general, because of the dependence of $F_{\text{IR}}$ on the grain size $a$, one cannot obtain analytical $a_{\text{disr}}$ as in Equation (21).

Thus, we first numerically calculate $\omega_{\text{RAT}}$ using Equation (13) and compare it with $\omega_{\text{disr}}$ to find $a_{\text{disr}}$ numerically, which is referred to as numerical results. Note that the disruption size is assumed to be the same for silicate and carbonaceous grains. The results are shown in the next section.

4. Grain Size Distribution and Extinction Curves Across Cosmic Time

4.1. Grain Size Distribution

The grain size distribution of dust is usually described by a power law,

$$\frac{dn}{da} = C_j n_H a^\alpha,$$

where $j$ denotes the grain composition (silicate and graphite), $C_j$ is the normalization constant, and $\alpha$ is the power slope.

For the standard ISM in our galaxy, Mathis et al. (1977) derived the slope $\alpha = -3.5$, $C_{\text{sil}} = 10^{-28.14} \, \text{cm}^{2.5} \, \text{erg}^{-1} \, \text{s}^{-1}$ for silicate grains, and $C_{\text{gra}} = 10^{-25.11} \, \text{cm}^{2.5} \, \text{erg}^{-1} \, \text{s}^{-1}$ for graphite grains. The size distribution has a lower cutoff of $a_{\text{min}} = 3.5 \, \mu m$ determined by thermal sublimation due to temperature fluctuations of very small grains (see, e.g., Draine et al. 2007), and an upper cutoff of $a_{\text{max}} = 0.25 \, \mu m$ (Mathis et al. 1977). To account for the potential existence of large grains in the ISM, we assume $a_{\text{max},\text{noRATD}} = 0.5 \, \mu m$ when $\text{RATD}$ is not accounted for. In the presence of $\text{RATD}$, the maximum size $a_{\text{max}}$ is determined by $\min(a_{\text{disr}}, a_{\text{max},\text{noRATD}})$ because $a_{\text{disr}}$ changes with redshift due to $\text{RATD}$ (see Equation (19)), the grain size distribution should change accordingly.

Figure 1 shows the variation in disruption size with redshift for different density ($n_H$) and tensile strength ($S_{\text{max}}$) obtained from numerical calculations (solid lines) and analytical results where the gas damping is disregarded (dotted lines). We consider the maximum redshift of $z_{\text{max}} = 10$, corresponding to the age of $t_{\text{age}} \sim 0.5 \, \text{Gyr}$. In general, analytical results obtained from Equation (21) converge to numerical results for sufficiently high $z$ with large radiation intensity but are lower than the numerical results for high density and low $z$ as a result of the effect of gas damping. For a given density, $a_{\text{disr}}$ decreases gradually with redshift. For the typical density of $n_H = 30 \, \text{cm}^{-3}$ and typical tensile strength of composite grains ($S_{\text{max}} = 10^5 \, \text{erg cm}^{-3}$), the disruption size decreases from $a_{\text{disr}} \sim 0.15 \, \mu m$ at $z = 0$ to $0.1 \, \mu m$ at $z = 2$, and $0.08 \, \mu m$ at $z = 5$. The disruption size is lower for grains with a lower tensile strength, as implied by Equation (18).

We also see that for the low-density cases (e.g., $n_H = 1, 10 \, \text{cm}^{-3}$), the disruption size changes slowly with $z$ as given by Equation (22) because IR damping dominates. However, its change with $z$ is stronger for a higher density ($n_H \approx 30, 100 \, \text{cm}^{-3}$) until the radiation field becomes sufficiently large for dominance of IR damping.

4.2. Extinction Curves and $R_V$

The extinction of starlight by interstellar dust at wavelength $\lambda$ in the unit of magnitude per H is calculated as

$$\frac{A_\lambda}{N_H} = \sum_{j=\text{sil,gra}} A_j \int_{a_{\text{min}}}^{a_{\text{max}}} \frac{n_d}{n_H} C_{\text{eff}}(a) \left( \frac{1}{n_H} \frac{dn}{da} \right) da,$$

where $N_H = \int n_H dz = n_H L$ with $L$ the path length is the column density, $dn/da$ is the grain size distribution of the dust
component \( j \), with the minimum size \( a_{\text{min}} \), and the maximum size \( a_{\text{max}} \) is taken to be \( a_{\text{disr}} \). \( C_{\text{ext}} \) is the cross section of the \( j \) dust component, which is calculated for oblate spheroidal grains with an axial ratio of 2 in Hoang et al. (2013) assuming an optical constant of astrosilicate and graphite (Draine & Lee 1984).

Using the disruption size obtained in Figure 1, we can calculate the wavelength-dependence extinction by dust that is modified by RATD using Equation (24).

Figure 2 shows the normalized extinction curves \( (A_{\lambda}/A_V) \) at different redshifts for different gas densities \( n_H \) and \( T_{\text{gas}} = 100 \) K, assuming that grains have a composite structure with \( S_{\text{max}} = 10^5 \text{erg cm}^{-3} \). In general, the UV extinction increases while the optical–NIR (near-IR) extinction decreases with redshift, resulting in steeper extinction curves. This arises from the effect of RATD that breaks large grains of \( a > a_{\text{disr}} \) into smaller ones. Indeed, since larger grains contribute more to extinction at optical–NIR wavelengths and small grains contribute more to UV extinction, the conversion of large to small grains decreases the optical–NIR extinction and increases UV extinction. One can see that the magnitude of the increase in UV extinction with redshift appears to be stronger for higher density. This can be seen from the variation of disruption size with \( z \) in Figure 1, where a larger variation in \( a_{\text{disr}} \) is seen for larger \( n_H \).

Using the obtained extinction curves, we calculate the ratio of total-to-selective extinction, \( R_V = A_V/(A_B - A_V) \). Figure 3 shows the decrease in \( R_V \) with \( z \) for different \( S_{\text{max}} \) and gas density. The shaded regions highlight low values of \( R_V < 2.5 \).

For a given density, \( R_V \) rapidly decreases with redshift. At a given redshift, \( R_V \) decreases with decreasing \( n_H \). For the typical strength of composite grains \( (S_{\text{max}} = 10^5 \text{erg cm}^{-3}) \), one obtains \( R_V < 2.5 \) for the considered gas densities, decreasing from \( R_V \sim 2-3.5 \) at \( z = 0 \) to \( R_V \sim 1.5 \) for \( z > 4 \) (see blue lines). For grains of strong material with \( S_{\text{max}} = 10^8 \text{erg cm}^{-3} \) (e.g., compact structure), one also see the decrease in \( R_V \) with redshift from \( R_V \sim 5 \) at \( z = 0 \) to \( R_V < 3.1 \) at \( z > 6 \). For a diffuse medium with \( n_H < 30 \text{ cm}^{-3} \), composite grains all have low \( R_V < 2 \) at high-\( z \). We find that the decrease in \( R_V \) occurs rapidly for \( z = 0-5 \). Above \( z = 5 \), the decrease in \( R_V \) is slower because the radiation intensity become sufficiently for IR damping to become dominant, and the disruption size slowly decreases with \( U \) (see Equation (21)).

In Figure 4 we show the variation in \( R_V \) with \( n_H \) for different redshift and tensile strength. The value of \( R_V \) increases with \( n_H \) for \( z < 4 \), but it becomes saturated at higher \( z \) due to the high radiation intensity that makes disruption independent of \( n_H \). For
4.3. Effect of Varying the Tensile Strength with Grain Structure

We now assume that grains smaller than \( a = a_{\text{core}} = 0.1 \, \mu m \) are compact and have a high tensile strength of \( S_{\text{max}} = 10^5 \, \text{erg cm}^{-3} \). Therefore, the disruption size cannot go below \( a_{\text{disr}} = a_{\text{core}} \), as shown in the left panel of Figure 5. We then run calculations of extinction curves and obtain \( R_V \), as shown in the right panel of Figure 5. The value of \( R_V \) decreases rapidly to its saturated value at \( R_V = 1.945 \) for two cases of a low strength of \( S_{\text{max}} = 10^5 \) and \( 10^6 \, \text{erg cm}^{-3} \). Grains with larger \( S_{\text{max}} \) cannot be disrupted down to the core radius, so \( R_V \) does not change.

5. Discussion

5.1. Smaller Grains at Higher Redshifts

We have applied the RATD mechanism to study the variation of the grain size distribution across cosmic time. Since the grain internal structures that determine the tensile strength are uncertain, we consider a range of tensile strength between \( 10^5 \) and \( 10^8 \, \text{erg cm}^{-3} \), which are implied by composite or core-mantle structures. We note that such structures are expected for interstellar dust as a result of various destruction and coagulation processes between the diffuse ISM and dense clouds (Mathis 1990; Draine & Hensley 2020).

Using the fact that the mean intensity of interstellar radiation increases with redshift (plausibly due to a higher star formation efficiency), we find that the disruption size that determines the maximum size of grains decreases rapidly with \( z \). Depending on the internal structure of grains, the maximum size can be larger for more compact grains of larger \( S_{\text{max}} \). We find that if grains have a typical composite structure of \( S_{\text{max}} = 10^5 \, \text{erg cm}^{-3} \), their maximum size is largest at \( a \sim 0.2 \, \mu m \) at \( z = 0 \) and rapidly decreases to \( a \leq 0.1 \, \mu m \) at higher \( z \). Therefore, dust at higher \( z \) is dominated by small grains. Alternatively, large grains at high-\( z \) would have more compact structures.

The disruption size also varies with the local gas density \( n_{H} \), but it becomes independent of \( n_{H} \) for \( z > 4 \) when the radiation intensity is sufficiently strong for rotational damping by IR emission to dominate the gas damping at \( n_{H} \lesssim 30 \, \text{cm}^{-3} \). We note that grain disruption is inefficient for dense molecular clouds without embedded stars where grain growth is driven by coagulation (Hirashita & Li 2013). If molecular clouds contain embedded sources, rotational disruption is still efficient in proximity of the sources, as found in Hoang et al. (2020).
5.2. Steeper Extinction Curves, Smaller RV, and Implications for Observations

Through RATD, large grains are converted into smaller ones. As a result, the extinction curve becomes steeper with increasing redshift (see Figure 2). The ratio of total-to-selective extinction, RV, is found to decrease with redshift. For composite grains, one has RV < 2.5 in the diffuse regions with n_H \sim 100 cm^{-3} (see Figure 3). For grains of higher tensile strength, RV could be larger than the standard RV = 3.1, but a decreasing trend is observed. At z = 0, composite grains are not disrupted for dense regions of n_H > 50 cm^{-3} and RV increases to larger than 3.1. However, at high-z, disruption is still efficient at such high density and RV only exceeds 3.1 when grains are compact (see Figure 4).

In starburst galaxies with star formation activities and supernova explosions, observations usually show peculiar extinction curves with a steep far-UV rise, SMC-like curve (Gordon et al. 1997). The SMC-like extinction curves are also observed toward the host galaxies of gamma-ray bursts (Schady et al. 2012; Heintz et al. 2019), quasars (Hopkins et al. 2004), and high-z star-forming galaxies (Reddy et al. 2018). Our theoretical modeling of extinction induced by RATD implies steep extinction curves with RV < 2.5 for z > 6 if grains do not have a compact structure with a tensile strength of S_{\text{max}} \gtrsim 10^8 \text{erg cm}^{-2} \text{max} (see Figure 3), which successfully reproduces the SMC-like extinction curves observed toward high-z galaxies using quasars or gamma-ray bursts.

5.3. Origins of Anomalous Dust Extinction Toward Supernovae Ia

Extinction curves toward supernovae (SN) Ia are known to be anomalous, with an unusually low value of RV \sim 1–2.5 and a mean value of \langle RV \rangle \approx 1.7 (Burns et al. 2014; Cikota et al. 2016) and \langle RV \rangle \approx 2.71 (Cikota et al. 2016). The exact origin of this low RV is unknown. Goobar (2008) suggested a multiple scattering model by circumstellar dust as a cause of low RV. The nondetection of NIR emission from SN 2014J by Spitzer (Johansson et al. 2017) as expected from hot circumstellar dust casts doubt on this scenario, however. The rotational disruption of grains by RATs proposed by Hoang et al. (2019) could reproduce such low values based on disruption induced by an SNe flash (Giang et al. 2020). In this scenario, there must exist a dust cloud within 4 pc from the source. The unique prediction of a disruption by an SNe flash is the variation in extinction and polarization of the SNe light with time.
Our results here show that when grains have a composite structure and are located in the diffuse environment ($n_H \leq 30$ cm$^{-3}$), $R_V$ is small, $\sim 1.9$–2.5 for $z \sim 0$–1 (see Figure 3), which adequately explains the estimated low $R_V$ values of SNe Ia. In particular, some SNe, including SNe 2006X, 2008fp, and 2014J, exhibit extreme values of $R_V < 1.5$ (see Hoang 2017). The adopted radiation intensity for main-sequence galaxies cannot produce these extreme values. When the mean intensity of these galaxies is enhanced by a starburst, for which the grain temperature can reach $T_d \sim 60$ K ($U \sim 10^8$) (Zavala et al. 2018), this corresponds to $z \sim 9$ when Equation (2) is used. For this radiation intensity, $R_V$ can be reproduced by RATD when grains have composite structures (see Figure 3). Note that because of its interstellar nature, the extinction and polarization curves implied by RATD do not vary with observational time (see the disruption by SNe light, Giang et al. 2020).

5.4. Space and Time Variation of $R_V$ and Implications for SNe Cosmology

The well-known crisis in cosmology is the tension in measurements of the Hubble constant using SNe Ia and cosmic microwave background (CMB) radiation. SNe Ia measurements report $H_0 = 74.03 \pm 1.42$ km s$^{-1}$ Mpc$^{-1}$ (Riess et al. 2019), whereas CMB measurements by Collaboration et al. (2020) report $H_0 = 67.4 \pm 0.5$ km s$^{-1}$ Mpc$^{-1}$. Moreover, Freedman et al. (2019) report $H_0 = 69.8 \pm 0.8$ km s$^{-1}$ Mpc$^{-1}$ using the tip of the red giant branch.

Dust extinction is critical for a precise measurement of $H_0$ using SNe Ia standardized candles. Brout & Scolnic (2020) suggested that the scatter in $H_0$ could be completely reproduced by allowing a variation in $R_V$. The recent analysis of González-Gaitán et al. (2020) also confirms the importance of the host galaxy dust. Since most SNe Ia are expected to explode in the low-density diffuse medium, it is unclear what causes the variation of $R_V$.

Our modeling results in Figure 3 show that because of rotational disruption by RATs, $R_V$ varies with the physical parameters of the local environment, including the gas density and the radiation field. It also changes with the grain structures. It is known that the ISM is turbulent (Armstrong et al. 1995), producing fluctuations in the gas density. Moreover, the local intensity depends on the distribution of stars. Therefore, the value of $R_V$ experiences strong fluctuations along the different lines of sight in the host galaxy. Such fluctuations in $R_V$ inevitably induce scatter in the inferred measurements of the Hubble constant.

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![Figure 4. Variation in $R_V$ with local gas density for different redshifts, assuming $S_{\text{max}} = 10^3$–$10^8$ erg cm$^{-3}$. The shaded area marks the region of low $R_V < 2.5$. The variation is most sensitive for $z \sim 0$–1 and becomes insensitive at high $z$ when the mean radiation intensity becomes sufficiently high.](image-url)
5.5. Implications for High-z Astrophysics

ALMA is revolutionizing our research on dust and gas in the early universe up to redshift $z \sim 10$ (see Bouwens et al. 2020). The relationship between the infrared (IRX) and UV slope ($\beta$), namely IRX-$\beta$, of the SED is a key parameter for estimating the SFR in galaxies (e.g., Bouwens et al. 2016). Therefore, an accurate extinction curve is critically important for reliable estimates of SFR. In light of our study, the extinction curves at high-$z$ are steeper than those in the standard Milky Way, and the steepness increases with redshift. Therefore, it poses a challenge for an accurate determination of star formation activity in early universe.

6. Summary

We study the variation of dust properties with redshift resulting from rotational disruption by RATs (RATD mechanism) induced by ISRF. The main results are summarized as follows:

1. The efficiency of RATD increases with redshift because the mean radiation intensity increases. The maximum size of the grain size distribution thus decreases with increasing redshift, but increases with the gas density. For $z > 4$, the disruption size of dust in the diffuse medium becomes independent of the density.

2. Rotational disruption converts large grains into smaller grains, thus, grains become smaller at higher redshifts. The resulting extinction curves become steeper, and the ratio of total-to-selective extinction, $R_V$, decreases rapidly with redshift.

3. When grains have composite structures of tensile strength $S_{mg} \lesssim 10^6$ erg cm$^{-3}$, $R_V$ is small, between 1.5 and 2.5, much smaller than the standard value of $R_V = 3.1$ in the Galaxy. This can reproduce the popular SMC-like extinction curves observed toward high-$z$ galaxies.

4. The unusually low values of $R_V \sim 1.5$–2.5 observed toward SNe Ia of $z < 1$ could be reproduced by RATD induced by ISRF if grains have composite structures, but the extreme values of $R_V < 1.5$ observed for several SNe Ia require an enhanced radiation field. Alternatively, it can be reproduced by RATD if there exist some nearby clouds within several parsecs.

5. The fluctuations in $R_V$ due to variation in the local gas density by interstellar turbulence, radiation intensity, and redshift inevitably affect the accurate measurements of the Hubble constant $H_0$. This might help to resolve the tension between local SNe measurements and early measurements using CMB.

6. The variation in dust properties also affects the SFR measured toward high-$z$ galaxies. Thus, one should account for the variation in extinction curves with $z$ to achieve accurate measurements.

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References

Armstrong, J. W., Rickett, B. J., & Spangler, S. R. 1995, ApJ, 443, 209
Bethermin, M., Daddi, E., Magdis, G., et al. 2015, A&A, 573, A113
Bouwens, R., Gonzalez-Lopez, J., Aravena, M., et al. 2020, ApJ, 902, 112
Bouwens, R. J., Aravena, M., Decarli, R., et al. 2016, ApJ, 833, 72
Brout, D., & Scollnic, D. 2020, arXiv:2004.10206
Burns, C. R., Stritzinger, M., Phillips, M. M., et al. 2014, ApJ, 789, 32
Calzetti, D. 2001, PASP, 113, 1449
Cikota, A., Deustua, S., & Marleau, F. 2016, ApJ, 819, 152
Collaboration, P., Aghanim, N., Akrami, Y., et al. 2020, A&A, 641, A6
Cowley, W. I., Bethermin, M., Lagos, C. d. P., et al. 2017, MNRAS, 467, 1231
del P Lagos, C., Bayet, E., Baugh, C. M., et al. 2012, MNRAS, 426, 2142
Dolginov, A. Z., & Mitrofanov, I. G. 1976, Ap&SS, 43, 128
Draine, B. T. 2003, ARA&A, 41, 241
Draine, B. T., Dale, D. A., Bendo, G., et al. 2007, ApJ, 663, 866
Draine, B. T., & Hensley, B. 2020, arXiv:2009.11314
Draine, B. T., & Lazarian, A. 1998, ApJ, 508, 157
Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89
