Rotational disruption of dust grains by high-velocity gas-grain collisions

Thiem Hoang,1,2 Hyeseung Lee,1

1Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea
2University of Science and Technology, Korea, (UST), 217 Gajeong-ro Yuseong-gu, Daejeon 34113, Republic of Korea

ABSTRACT

Dust grains moving at hypersonic velocities of \( v_d \gtrsim 100 \text{ km s}^{-1} \) through an ambient gas are known to be destroyed efficiently by nonthermal sputtering. Yet, previous studies of nonthermal sputtering disregarded the fact that the grain can be spun-up to suprathermal rotation by stochastic gas-grain collisions. In this paper, we show that such a suprathermal rotation results in the disruption of the small grain into molecules because the induced centrifugal stress can exceed the maximum tensile strength of grain material, \( S_{\text{max}} \). We term this mechanism rotational disruption. We find that rotational disruption is more efficient than nonthermal sputtering in destroying small dust grains of nonideal internal structures moving with velocities of \( v_d > 100 \text{ km s}^{-1} \). The ratio of rotational disruption to sputtering time is \( \tau_{\text{disr}}/\tau_{\text{sp}} \sim 0.2(S_{\text{max}}/10^9 \text{ erg cm}^{-3})(Y_{\text{sp}}/0.1)(a/0.01 \mu\text{m})^3(300 \text{ km s}^{-1}/v_d)^2 \) where \( a \) is the radius of spherical grains, and \( Y_{\text{sp}} \) is the sputtering yield. We discuss the implication of this mechanism for the destruction of hypersonic grains accelerated by radiation pressure as well as grains in fast shocks. Our results suggest that the destruction of dust grains in fast shocks of supernova remnants is more efficient than previously predicted by sputtering, which seems to be supported by the higher fraction of dust destruction observed in fast shocks of core-collapse supernovae.

Keywords: dust, extinction, shock waves, supernova remnants

1. INTRODUCTION

The motion of dust grains at high velocities above 100 km s\(^{-1}\) through the ambient gas (hereafter hypersonic motion) is common in the universe. Various physical processes can accelerate dust grains to hypersonic velocities, including radiation pressure induced by strong radiation sources (e.g., late-type stars, supernovae, and active galactic nuclei; Goldreich & Scoville 1976; Netzer & Elitzur 1993) and shock waves. Moreover, charged grains can be accelerated to high velocities in interstellar shocks of supernova remnants via betatron and Fermi acceleration mechanisms (Epstein 1980; Ellison et al. 1997). Magnetohydrodynamic turbulence is found to accelerate charged dust grains to high velocities (Yan et al. 2004; Hoang et al. 2012). In particular, newly formed dust grains in the supernova ejecta move hypersonically through the ambient gas before injected into the diffuse interstellar medium.

Hypersonic grain motion is thought to play an important role for a wide range of astrophysical phenomena such as galactic winds (e.g., Ishibashi & Fabian 2015), dust transport from the galaxy to the circumgalactic and intergalactic medium (Ferrara et al. 1991; Aguirre et al. 2001a; Aguirre et al. 2001b; Bianchi & Ferrara 2005). Therefore, the critical question is whether dust grains can survive during the transport from the galaxy into the intergalactic medium (IGM). The survival of dust in the supernova ejecta is crucially important for quantifying the dust budget in the universe.

Nonthermal sputtering is believed to be a dominant mechanism for destruction of hypersonic grains (Draine & Salpeter 1979a). Thus, understanding the physics of sputtering is critically important for quantitative understanding of the formation and destruction of cosmic dust (see, e.g., Nozawa et al. 2006). The underlying physics of sputtering is that an impinging ion/atom can eject some target atoms from the grain surface via nuclear-nuclear or electronic interactions (Sigmund 1981).

In fast shocks of velocities \( v_{\text{sh}} \gtrsim 100 \text{ km s}^{-1} \), nonthermal sputtering is usually referred to explain the destruction of dust grains (Draine & Salpeter 1979a; Jones et al. 1994; Draine 1995). Nevertheless, observations show that the fraction of dust destroyed in fast shocks is higher than predicted by theoretical predictions based on sputtering (Williams et al. 2006; Sankrit et al. 2010; Zhu et al. 2019). This motivates us to look for physical effect ignored in the current theory of sputtering.

Indeed, previous studies of nonthermal sputtering disregarded the fact that the grain can be spun-up to suprathermal rotation by stochastic gas-grain collisions.
as pointed out by Gold (1952) and numerically demonstrated through Monte Carlo simulations by Purcell & Spitzer (1971). Recently, Hoang & Tram (2019) studied the effect of gas bombardment for nanoparticles drifting in steady-state shocks and found that the smallest nanoparticles (size below 2 nm) can be destroyed by centrifugal stress in slow shocks of $v_{sh} < 50$ km s$^{-1}$. In this paper, we aim to study the effect of rotational disruption for high-velocity gas-grain collisions and compare the obtained results with the traditional sputtering mechanism.

The structure of our paper is as follows. In Section 2, we study the spin-up and disruption of grains by stochastic torques upon gas-grain collisions, and we compare rotational disruption with nonthermal sputtering in Section 3. Section 4 is devoted to discussing the implications of our study for dust destruction in fast shocks and grains accelerated by radiation pressure and its transport into the IGM. The summary of our main findings is presented in Section 5.

2. ROTATIONAL DISRUPTION BY GAS-GRAIN COLLISIONS

2.1. Spin-up by stochastic torques from gas-grain collisions

We consider a dust grain moving through the ambient gas of atomic hydrogen of temperature $T_{\text{gas}}$ and number density $n_{\text{H}}$. Let define isothermal Mach sonic number $s_{d} = v_{d}/v_{T}$ where $v_{T} = (2kT_{\text{gas}}/m_{\text{H}})^{1/2} \approx 1.2T_{2}^{1/2}$ km s$^{-1}$ with $T_{2} = T_{\text{gas}}/100$ K is the thermal gas velocity. For the supersonic regime of $s_{d} \gg 1$ considered in this paper, the effect of thermal gas collisions is subdominant and can be ignored. Let $a$ be the radius of spherical grains.

Now, let us estimate the rotational excitation of grains due to gas collisions, which is essentially similar to Gold (1952). Each atom colliding with the grain surface at radius $r$ induces an impulsive torque of $r \times m_{\text{H}}v$, such that the increase of $\langle \delta J \rangle^{2}$ from each impact becomes

$$\langle \delta J \rangle^{2} = \langle rm_{\text{H}}v_{d} \rangle^{2} = m_{\text{H}}^{2}v_{d}^{2}r^{2}. \tag{1}$$

When averaging the the grain surface, one has $\langle r^{2} \rangle = a^{2}/2$, and Equation (1) becomes

$$\langle \langle \delta J \rangle^{2} \rangle = \frac{1}{2}m_{\text{H}}^{2}v_{d}^{2}a^{2}, \tag{2}$$

which yields the rotational angular velocity acquired by a single collision:

$$\delta \omega = \langle \langle \delta J \rangle^{2} \rangle^{1/2}/I \approx 1.6 \times 10^{7}a_{-6}^{-4}v_{3} \text{ rad s}^{-1}, \tag{3}$$

where the inertia moment $I = 8\pi \rho a^{3}/15$ with $\rho$ the grain mass density, $a_{-6} = a/(10^{-6} \text{ cm})$, and $v_{3} = v_{d}/(10^{3} \text{ km s}^{-1})$.

Using the random walk theory for stochastic collisions, one can derive the total increase of squared angular momentum per unit of time as follows:

$$\frac{\langle \langle \delta J \rangle^{2} \rangle}{\Delta t} = R_{\text{coll}} \langle \delta J \rangle^{2} = n_{\text{H}}v_{d}\pi a^{2}m_{\text{H}}^{2}v_{d}^{2}a^{2}/2, \tag{4}$$

where the collision rate $R_{\text{coll}} = n_{\text{H}}v_{d}\pi a^{2}$ has been used.

After traversing a time interval $\Delta t$, the total average increase of the squared angular momentum is equal to

$$\langle \langle \delta J \rangle^{2} \rangle = \frac{n_{\text{H}}m_{\text{H}}^{2}v_{d}^{2}\pi a^{4}}{2}\Delta t. \tag{5}$$

The $\text{rms}$ angular velocity of grains can now be calculated using the total angular momentum $\Delta J$ from Equation (5):

$$\omega_{\text{rms}}^{2} = \langle \omega^{2} \rangle \sim \langle \langle \delta J \rangle^{2} \rangle /I^{2} = \frac{n_{\text{H}}m_{\text{H}}^{2}v_{d}^{2}\pi a^{4}}{2I^{2}}\Delta t. \tag{6}$$

A rotating grain experiences rotational damping due to sticking collision with gas atoms, followed by thermal evaporation of atoms that carry away part of the grain angular momentum (see e.g., Draine & Lazarian 1998). Consider a grain rotating along the $z$-axis with angular velocity $\omega_{z}$. The angular momentum carried away by an H atom from the grain surface is given by

$$\delta J_{z} = I_{m}\omega_{z} = m_{\text{H}}r^{2}\omega_{z} = m_{\text{H}}a^{2}\sin^{2}\theta\omega_{z}, \tag{7}$$

where $r$ is the distance from the atom to the spinning axis $z$, $I_{m} = m_{\text{H}}r^{2}$ is the inertial moment of the hydrogen atom of mass $m_{\text{H}}$, $\theta$ is the angle between the $z$-axis and the radius vector, and $r = a\sin \theta$ is the projected distance to the center. Assuming the isotropic distribution of $\theta$ for atoms leaving the grain, one can replace $\sin^{2} \theta =< \sin^{2} \theta >= 2/3$, which give rise to

$$\langle \delta J_{z} \rangle = \frac{2}{3}m_{\text{H}}a^{2}\omega_{z}. \tag{8}$$

Using the collision rate of atomic gas, $R_{\text{coll}}$, one can derive the mean decrease of grain angular momentum per unit of time is

$$\left< \frac{\Delta J_{z}}{\Delta t} \right>_{\text{H}} = -R_{\text{coll}} \langle \delta J_{z} \rangle = -\frac{2}{3}m_{\text{H}}\pi a^{4}\omega_{z}<v> = -\frac{I\omega_{z}}{r_{\text{H}}}. \tag{9}$$

For the drift velocity with $v \gg v_{T}$, one has $<v> = v_{d}$. Therefore, the rotational damping time is

$$\tau_{\text{H}} = \frac{3I}{2n_{\text{H}}m_{\text{H}}\pi a^{4}v_{d}} = \frac{4\rho a}{5n_{\text{H}}m_{\text{H}}v_{d}} \approx 572\frac{\rho a_{-6}}{v_{3}a_{-1}} \text{ yr}. \tag{10}$$
where $n_1 = n/(10 \text{ cm}^{-3})$, $v_2 = v_d/(100 \text{ km s}^{-1})$.

Rapidly spinning dust grains emit strong electric dipole radiation (Draine & Lazarian 1998), which also damps the grain rotation on a timescale of

$$\tau_{\text{ed}} = \frac{3I_0^2c^3}{\mu^2kT_{\text{gas}}} \simeq 2.25 \times 10^8 \left( \frac{n_{-6}}{3.8 \beta} \right) \left( \frac{100 \text{ K}}{T_{\text{gas}}} \right) \text{yr} \tag{11}$$

where $\mu$ is the grain dipole moment and $\beta = \beta/(0.4D)$ with $\beta$ being the dipole moment per structure due to polar bonds present in the dust grain (Draine & Lazarian 1998; Hoang et al. 2010; Hoang et al. 2016).

Comparing $\tau_{ed}$ with $\tau_\text{H}$, one can see that, for not very small grains ($a > 1 \text{ nm}$), the electric dipole damping time is longer than the gas damping time.

Due to the rotational damping, the grain looses angular momentum on a timescale of $\tau_\text{H}$. Therefore, the rms angular velocity is equal to

$$\omega_{\text{rms}}^2 = \left( \frac{\Delta_J^2}{I^2} \right) = \frac{nHm_H^2v_3^3\pi a^4}{2I^2} \tau_\text{H}, \tag{12}$$

which can be rewritten as

$$\frac{\omega_{\text{rms}}^2}{\omega_T^2} = \frac{s_d^2}{2}, \tag{13}$$

where the thermal angular velocity

$$\omega_T = \left( \frac{3kT_{\text{gas}}}{I} \right)^{1/2} \simeq 9 \times 10^7 a_{-6}^{-5/2} T_2^{-1/2} \rho_{-1}^{-1/2} \text{ rad s}^{-1}. \tag{14}$$

### 2.2. Rotational Disruption Mechanism

The basic idea of the rotational disruption mechanism is as follows. A spherical dust grain rotating at velocity $\omega$ develops a centrifugal stress due to centrifugal force, which scales as $S = \rho a^2 \omega^2/4$ (Hoang et al. 2019). When the rotation rate increases to a critical limit such that the tensile stress induced by centrifugal force exceeds the maximum tensile stress, the so-called tensile strength of the material, the grain is disrupted instantaneously. The critical angular velocity for the disruption is given by

$$\omega_{\text{cri}} = \frac{2}{a} \left( \frac{S_{\text{max}}}{\rho} \right)^{1/2} \simeq 10^9 a_{-6}^{-1} \rho_{-1}^{-1/2} S_{\text{max},9} \text{rad s}^{-1}, \tag{15}$$

where $S_{\text{max}}$ is the tensile strength of dust material and $S_{\text{max},9} = S_{\text{max}}/10^9 \text{ erg cm}^{-3}$ is the tensile strength in units of $10^{10} \text{ erg cm}^{-3}$.\(^1\)

\(^1\) An alternative unit of the tensile strength is dyne/cm\(^2\), but in this paper we use the unit of erg cm\(^{-3}\) for $S_{\text{max}}$.

The exact value of $S_{\text{max}}$ depends on the dust grain composition and structure. Compact grains can have higher $S_{\text{max}}$ than porous/composite grains. Ideal material without impurity, such as diamond, can have $S_{\text{max}} \gtrsim 10^{11} \text{ erg cm}^{-3}$ (see Hoang et al. 2019 for more details). In the following, grains with $S_{\text{max}} \gtrsim 10^{10} \text{ erg cm}^{-3}$ are referred to as strong materials, and those with $S_{\text{max}} < 10^{10} \text{ erg cm}^{-3}$ are called weak materials.

### 2.3. Disruption time and disruption size

The time required to spin-up a grain of size $a$ to $\omega_{\text{cri}}$, so-called rotational disruption time, is evaluated as follows:

$$\tau_{\text{disr}} = \frac{J_{\text{cri}}^2}{(\Delta J)^2/(\Delta t)} = \frac{(l \omega_{\text{cri}})^2}{n_H m_H^2 v_3^3 a^4} \frac{10^9 \text{ yr}}{100 \text{ km s}^{-1}} \tag{16}$$

We note that rotational disruption only occurs when the required time is shorter than the rotational damping time. Let $a_{\text{disr}}$ be the grain diameter size as determined by $\tau_{\text{disr}} = \tau_\text{H}$. Thus, one obtains:

$$a_{\text{disr}} = \frac{(45kT_{\text{gas}} s_d^2)^{1/3}}{64\pi S_{\text{max}}^{1/3}} \simeq 0.00372 S_{\text{max},9}^{2/3} S_{\text{max},9}^{1/3} \mu \text{m} \tag{17}$$

which reveals that rotational disruption is efficient for small grains only.

For a given grain size, the critical speed required for disruption is given by

$$s_d \gtrsim \left( \frac{64 \pi a^3 S_{\text{max}}}{45kT_{\text{gas}}} \right)^{1/2} \simeq 560 a_{-6} S_{\text{max},9} T_2^{-1/2} \text{ m s}^{-1}, \tag{18}$$

which yields

$$v_d \gtrsim \left( \frac{128 \pi a^3 S_{\text{max}}}{45 m_H} \right)^{1/2} \simeq 720 a_{-6} S_{\text{max},9} T_2^{1/2} \text{ km s}^{-1}. \tag{19}$$

### 2.4. Slowing-down time by gas drag force

For hypersonic grains, the main gas drag arises from direct collisions with gas atoms, and the Coulomb drag force is subdominant (Draine & Salpeter 1979b). Assuming the sticky collisions of atoms followed by their thermal evaporation, the decrease in the grain momentum is equal to the momentum transferred to the grain in the opposite direction:

$$\frac{dP}{dt} = n_H v_d \times n_H v_d \pi a^2. \tag{20}$$

The gas drag time is given by

$$\tau_{\text{drag}} = \frac{m_{gr} v_d}{dP/dt} = \frac{4 \pi \rho a^3 v_d}{3 \pi a^2 m_H v_d^2 m_H} \simeq \frac{4 a}{3 m_H m_H v_d} \approx 763 \left( \frac{\rho_{-6}}{n_1 v_2} \right) \text{ yr}. \tag{21}$$
Comparing Equations (21) with (16) one can see that the disruption occurs much faster than the drag time for \( v > 100 \text{km s}^{-1} \) and small grains of \( a < 0.01 \mu m \).

3. COMPARISON OF ROTATIONAL DISRUPTION WITH NONTHERMAL SPUTTERING

Dust grains moving at high velocities through the ambient gas are destroyed by nonthermal sputtering by gas-grain collisions (e.g., Draine & Salpeter 1979a; Jones et al. 1994). Let \( Y_{sp} \) be the average sputtering yield per impinging atom (i.e., H and He) with velocity \( v_d \). Note that the sputtering by He impacts is higher than that of H due to their higher momentum transfer during the collisions (see e.g., Draine 1995).

We first show that rotational disruption is faster than nonthermal sputtering. Indeed, from Equation (3) one can see that a single collision can spin up the grain to \( \delta \omega \sim 10^6 a^{-4} v_d d \text{rad s}^{-1} \). Thus, to spin-up the 0.01 \( \mu m \) grain to the disruption limit, \( \omega_{cri} \sim 10^9 \text{rad s}^{-1} a_{max,9}^{1/2} \), it only requires \( N_{disr} \sim (\omega_{cri}/\delta \omega)^2 \sim 10^4 \) random collisions. However, nonthermal sputtering of yield \( Y_{sp} \sim 0.1 \) requires \( N_{st}/Y_{sp} \sim 10^6 \) collisions to completely destroy the grain.

Let us now compare the sputtering timescale with the disruption time. The rate of the grain mass loss due to nonthermal sputtering is given by

\[
\frac{4\pi \rho a^2 da}{dt} = n_H v_d \pi a^2 Y_{sp} m_H. \tag{22}
\]

The characteristic timescale of grain destruction by nonthermal sputtering for a grain of size \( a \) is defined by

\[
\tau_{sp} = \frac{a}{da/dt} \sim 2.4 \times 10^3 \rho \left( \frac{a-6}{n_1 v_2} \right) \times \left( \frac{0.1}{Y_{sp}} \right) \text{ yr}. \tag{23}
\]

For a constant \( Y_{sp} \), the sputtering time decreases as \( 1/v_d \). In contrast, the rotational disruption time \( \tau_{disr} \) decreases as \( 1/v_d^4 \) (see Eq. 16). Therefore, the rotational disruption is more efficient than sputtering for increasing the grain velocity.

From Equations (16) and (23) one obtains the ratio of rotational disruption to nonthermal sputtering:

\[
\frac{\tau_{disr}}{\tau_{sp}} \sim 2 S_{max,9} \left( \frac{Y_{sp}}{0.1} \right) \left( \frac{a_{disr}^{-6}}{v_2^2} \right), \tag{24}
\]

which reveals that grain disruption is more efficient than sputtering when \( t_{disr}/t_{sp} < 1 \) for small grains or high drift velocity.

Figure 1 shows the rotational disruption time compared to the various timescales, including non-thermal sputtering, gas drag, and rotational damping, assuming the different velocities and tensile strength. For small grains of \( a = 0.01 \mu m \), rotational disruption is faster than sputtering for velocities of \( v_d > 10^5 \text{km s}^{-1} \) if the dust material is very strong with \( S_{max} = 10^{10} \text{erg cm}^{-3} \). For weak materials of \( S_{max} \sim 10^7 \text{erg cm}^{-3} \) (e.g., fluffy grains), the disruption is much faster than gas drag and sputtering at lower velocities of \( v > 50 \text{km s}^{-1} \). For large grains of \( a = 0.1 \mu m \), the disruption is still efficient for weak material of \( S_{max} \sim 10^7 \text{erg cm}^{-3} \) at \( v > 100 \text{km s}^{-1} \), but it is inefficient for strong materials. Note that the sputtering time is longer than the damping time, which means that the grain is not entirely destroyed by sputtering before it is coupled to the gas by gas drag.

Figure 2 shows the disruption timescale as a function of the grain size compared to that of the various processes, assuming the different drift velocity. The rotational disruption is faster than gas drag as well as sputtering for small grains and high velocities. At very high velocity of \( v_d = 1000 \text{km s}^{-1} \), the rotational disruption can be important for large grains of \( a < 0.1 \mu m \).

One of the feature of nonthermal sputtering is that the sputtering yields peaks around \( v \sim 100 - 200 \text{km s}^{-1} \) for H and He bombardment due to the maximum cross-section of nuclear-nuclear interaction. Beyond the peak, the sputtering yield gradually decreases with increasing the velocity. On the other hand, the rotation rate spin-up by stochastic torques increases with increasing the velocity as \( s_d \), and the tensile stress increases as \( s_d^2 \). As a result, the rotational disruption becomes more efficient at high velocities. In particular, for composite grains with tensile strength \( S_{max} < 10^9 \text{erg cm}^{-3} \), the rotational disruption is efficient for \( v > 50 \text{km s}^{-1} \), assuming a typical grain size of \( a = 0.1 \mu m \).

Both rotational disruption and sputtering time decrease with decreasing the grain size. However, the rotational disruption decreases much faster, as \( \tau_{disr} \propto a^4 \) compared to the linear dependence of \( \tau_{sp} \). Therefore, the destruction of grains by rotational disruption is dominant over thermal sputtering for grains of size \( a < a_{disr} \). For larger grains, the disruption does not occur, but sputtering still can occur and take over.

While nonthermal sputtering does depend on the internal structure of grains (e.g., only on the binding energy of target atoms), rotational disruption critically depends on the tensile strength \( S_{max} \). Our results show that the chance for survival increases with the tensile strength. Therefore, ideal material like diamond or graphite of compact structure could survive the rotational disruption.
Figure 1. The rotational disruption time vs. the grain velocity for the different grain sizes and tensile strength $S_{\text{max}}$. The timescales of nonthermal sputtering with various values of $Y_{sp}$, gas drag, rotational damping, and electric dipole damping are overplotted for comparison. The typical parameters of the standard interstellar medium $n_H = 10^{-3}$ cm$^{-3}$ and $T_{\text{gas}} = 100$ K are assumed.

Figure 3 shows the grain disruption size as a function of the grain velocity for the different value of tensile strength. The disruption size increases with increasing $v_d$. For $v_d = 10^4$ km s$^{-1}$, even large grains of $a \sim 0.5 \mu$m can be disrupted if they are made of fluffy structure with $S_{\text{max}} < 10^7$ erg cm$^{-3}$. Grains of ideal structures are destroyed only for $a < 0.1 \mu$m.

As shown in Figure 2, rotational disruption only occurs when the disruption time is shorter than the drag time. Using Equation (16) and (21), one can derive the critical size for the disruption, $a_{\text{disr,1}}$, that satisfies the equation $\tau_{\text{disr,1}} = \tau_{\text{drag}}$ as follows:

$$a_{\text{disr,1}} = \left( \frac{125 \, m_H \, v^2}{192 \, \rho \, S_{\text{max}}} \right)^{1/3} \approx 0.003 \hat{\rho}^{-1/3} v_2^{2/3} S_{\text{max}}^{-1/3} \mu$m.  \quad (25)$$

Comparing Equations (25) with (17) one can see that the the disruption sizes determined by the gas drag is slightly higher than rotational damping.

4. DISCUSSION

4.1. The importance of grain internal structures for dust destruction by gas-grain collisions

Internal structures (compact vs. porous) of dust grains are essential for dust absorption and emission (Guillet et al. 2017). The grain internal structure determines the mechanical strength of grains as measured by tensile strength. Indeed, grain internal structures are found to play an important role for grain coagulation (Dominik & Tielens 1997). However, this property is previously ignored in the destruction process by gas-grain collisions (thermal and nonthermal processes).
Figure 2. Same as Figure 1, but showing the timescale vs. grain size, assuming the different grain velocities. The rotational damping by electric dipole emission $\tau_{ed}$ is much longer than the gas damping time for the considered grain sizes.

Figure 3. Grain disruption size vs. grain velocity assuming the different tensile strength of grain material.

Very recently, with the discovery of Radiative Torque Disruption (RATD) mechanism (Hoang et al. 2019), the grain tensile strength is crucially important in determining the upper cutoff of the grain size distribution (Hoang 2019). Our present study reveals that the tensile strength also plays a critical role in the dust destruction by gas-grain collisions. Small grains of fluffy structures with low tensile strength ($S_{\text{max}} < 10^9 \text{erg cm}^{-3}$) can be destroyed more efficiently than nonthermal sputtering when moving at high velocities through the gas.

4.2. Destruction of grains accelerated by radiation pressure and implications for IGM

Dust grains can be accelerated to hypersonic velocities by radiation pressure from intense radiation sources such as massive OB stars, SNe, and AGNs (see, e.g., Hoang 2017). The maximum gas column density that a small grain of size $a < a_{\text{disr}}$ can traverse before being disrupted by
Rotational disruption is estimated as

\[
N_{\text{max,disr}} = n_H v_d \tau_{\text{disr}} \\
\simeq 1.5 \times 10^{18} a_{-6}^{4} S_{\text{max,9}} v_d^{-2} \text{ cm}^{-2}.
\] (26)

Similarly, one can evaluate the maximum distance determined by sputtering as

\[
N_{\text{max,sp}} = n_H v_d \tau_{\text{sp}} \simeq 7.6 \times 10^{18} a_{-6} S_{\text{sp,-1}} \text{ cm}^{-2}.
\] (27)

where \(S_{\text{sp,-1}} = Y_{\text{sp}}/(0.1)\).

The grain can only traverse a distance of \(D_{\text{max,disr}} = N_{\text{max,disr}}/n_H \sim 10^4(50/n_1)S_{\text{max,9}} a_{-6} v_d^{-2} \text{ AU before being disrupted by centrifugal stress.}\)

Observations show the presence of dust in the circumgalactic medium (CGM) and intergalactic medium (IGM). The underlying mechanism to the existence of dust in the CGM and IGM is due to radiation pressure that expels grains at high speeds. The enrichment of metals and dust in the IGM is believed to arise from two main routes, including galactic winds driven by supernovae and the injection of galactic grains moving at high velocities of \(v_d > 100 \text{ km s}^{-1}\) accelerated by radiation pressure (see e.g., Bianchi & Ferrara 2005). Ferrara et al. (1991) find that radiation pressure from starlight can accelerate grains to \(v_d \sim 100 – 600 \text{ km s}^{-1}\) from the Galaxy to galactic halo over a timescale of Myr. At such high velocities, small grains are efficiently destroyed by nonthermal sputtering. In this paper, we found that small grains can be destroyed faster than nonthermal sputtering, which reduces the escape fraction of grains expelled into the IGM.

4.3. Rotational disruption in hot gas

In the post-shock regions or ionized plasma, gas can be heated to very high temperatures of \(T_{\text{gas}} > 10^6 \text{ K}\). In such a hot gas, thermal collisions with protons can spin-up dust grains to extremely fast rotation with \(\omega_{\text{rot}} = \omega_T\), resulting in the rotational disruption (Draine & Salpeter 1979b). Using the disruption criteria, one obtains disruption size for a given \(T_{\text{gas}}\) as given by

\[
\alpha_{\text{disr}} = \left( \frac{45k T_{\text{gas}}}{32 \pi S_{\text{max}}} \right)^{1/3} \simeq 0.02 S_{\text{max,9}}^{-1/3} \left( \frac{T_{\text{gas}}}{10^8 \text{ K}} \right)^{1/3} \mu\text{m}. \] (28)

The critical gas temperature required for rotational disruption in a hot plasma is given by

\[
T_{\text{gas}} \gtrsim \left( \frac{32 \pi a^3}{45k} \right) S_{\text{max}} \simeq 1.6 \times 10^7 a_{-6} S_{\text{max,9}} \text{ K},
\] (29)

which implies that the rotational disruption is important for \(T_{\text{gas}} \sim 10^6 \text{ K}\) if grains are as small as 0.01 \(\mu\text{m}\) and made of weak materials (\(S_{\text{max}} < 10^9 \text{ erg cm}^{-3}\)).

Figure 4 shows the disruption size as a function of the gas temperature. Small grains are destroyed by rotational disruption so that dust grains in hot plasma are only larger than \(\alpha_{\text{disr}}\). Large grains with weak structures can be destroyed by rotational disruption for temperatures \(T_{\text{gas}} \sim 10^9 \text{ K}\). So, we predict that dust grains in very hot gas likely have a compact structure of high tensile strength.

4.4. Rotational disruption of dust grains in fast shocks

Shocks are ubiquitous in the interstellar medium, which includes slow shocks of velocities \(v_{sh} < 50 \text{ km s}^{-1}\) driven by the outflow of young stars, stellar winds, and jets, and fast shocks of velocities \(v_{sh} > 100 \text{ km s}^{-1}\) driven by supernova blast waves. Grain shattering dominates for slow shocks (Draine & Salpeter 1979a; see Draine 1995), but for fast shocks, sputtering is dominant in destroying refractory grains of small sizes (Tielens et al. 1994).

A new understanding of dust destruction in shocks is presented in Hoang & Tram (2019) and Tram & Hoang (2019). For steady-state shocks, Hoang & Tram (2019), for the first time, found that nanoparticles of size \(a < 2 \text{ nm}\) can be disrupted into molecules due to centrifugal stress. For the same grain size, sputtering is found to have a lower destruction rate. In this paper, we found that rotational disruption is dominant over sputtering for fast shocks if grains are small or made of weak materials.

Fast shocks are very common in core-collapse supernova due to the interaction of ejecta with the surround-
ing environment (see e.g., Nozawa et al. 2006). Newly formed dust grains in the supernova ejecta are subject to reverse shocks and move at velocity of \(2/((\gamma + 3)v_{sh})\) with adiabatic index \(\gamma = 5/3\) relative to the gas (see e.g., Dwek et al. 1996; Bianchi & Schneider 2007). Traditionally, thermal and non-thermal sputtering is established to be a main destruction mechanism of dust, which controls the dust evolution in the early universe (Nozawa et al. 2006). In light of our results, rotational disruption dominates over sputtering for very fast shocks (i.e., \(v_{sh} > 500\) km s\(^{-1}\)). Therefore, newly formed dust in supernova remnants (SNRs) is expected to have deficiency of small and very small grains of size \(a < a_{\text{disr}}\) due to rotational disruption, which is in agreement with observations (see Micelotta et al. 2018 and reference therein).

Observational data by Williams et al. (2006) and Zhu et al. (2019) show that for the fraction of dust destructed in fast shocks of core-collapse supernova is higher than theoretical predictions based on sputtering. The authors appeal to the porous structure of dust grains to enhance the sputtering rate. However, this observational puzzle can be explained by rotational disruption.

Finally, we note that in this paper, we have assumed spherical grains and disregarded the effect of regular mechanical torques acting on grains of irregular shapes (Lazarian & Hoang 2007; Das & Weingartner 2016; Hoang et al. 2018). The latter is expected to be more efficient.

5. SUMMARY

We study the destruction of dust due to gas-grain collisions at high speeds. Our results are summarized as follows:

• We find that small grains or large grains having fluffy structures can be disrupted by centrifugal stress within rapidly spinning grains due to stochastic gas-grain collisions when the relative grain velocity is \(v_d \gtrsim 100\) km s\(^{-1}\).

• We compare the timescale of rotational disruption with sputtering timescale and find that the rotational disruption is much more efficient than sputtering for grain velocities \(v_d > 100\) km s\(^{-1}\). The ratio of rotational disruption to sputtering time is \(\tau_{\text{disr}}/\tau_{sp} \sim 0.2S_{\text{max}}9Y_{sp}^{-1}a_{\text{disr}}^{3/6}(300\) km s\(^{-1}/v_d)^{-2}\).

• We discuss the implication of our study for the origin of intergalactic dust and find that small grains are likely disrupted before injecting into the IGM. Large grains of \(a \sim 0.05 - 0.1\) \(\mu\)m of weak material are disrupted, but strong material such as compact grains can survive and reach the IGM.

• Our results demonstrate that the rotational disruption appears to be dominant destruction mechanism of refractory small grains in fast shocks of \(v_{sh} > 100\) km s\(^{-1}\), instead of non-thermal sputtering as previously thought. This enhanced dust destruction rate appears to be consistent with dust destruction measured from fast shocks of core-collapse supernovae.

ACKNOWLEDGMENTS

We are grateful to A. Lazarian for his encouragement. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (2019R1A2C1087045).

REFERENCES

Aguirre, A., Hernquist, L., Katz, N., Gardner, J., & Weinberg, D. 2001a, ApJ, 556, L11
Aguirre, A., Hernquist, L., Schaye, J., et al. 2001b, ApJ, 561, 521
Bianchi, S., & Ferrara, A. 2005, MNRAS, 358, 379
Bianchi, S., & Schneider, R. 2007, MNRAS, 378, 973
Das, I., & Weingartner, J. C. 2016, MNRAS, 457, 1958
Dominik, C., & Tielens, A. G. G. M. 1997, ApJ, 480, 647
Draine, B. T. 1995, Astrophysics and Space Science, 233, 111
Draine, B. T., & Lazarian, A. 1998, ApJ, 508, 157
Draine, B. T., & Salpeter, E. E. 1979a, ApJ, 231, 438
Draine, B. T., & Salpeter, E. E. 1979b, ApJ, 231, 77
Dwek, E., Foster, S. M., & Vancura, O. 1996, ApJ, 457, 244
Ellison, D. C., Drury, L. O., & Meyer, J.-P. 1997, ApJ, 487, 197
Epstein, R. I. 1980, MNRAS, 193, 723
Ferrara, A., Ferrini, F., Franco, J., & Barsella, B. 1991, Astrophysical Journal, 381, 137
Gold, T. 1952, MNRAS, 112, 215
Goldreich, P., & Scoville, N. 1976, ApJ, 205, 144
Guillet, V., Fanciullo, L., Verstraete, L., et al. 2017, A&A
Hoang, T. 2017, ApJ, 847, 77
Hoang, T. 2019, ApJ, 876, 13
Draine, T. S., & Salpeter, E. E. 1979b, ApJ, 231, 77
Dwek, E., Foster, S. M., & Vancura, O. 1996, ApJ, 457, 244
Ellison, D. C., Drury, L. O., & Meyer, J.-P. 1997, ApJ, 487, 197
Epstein, R. I. 1980, MNRAS, 193, 723
Ferrara, A., Ferrini, F., Franco, J., & Barsella, B. 1991, Astrophysical Journal, 381, 137
Gold, T. 1952, MNRAS, 112, 215
Goldreich, P., & Scoville, N. 1976, ApJ, 205, 144
Guillet, V., Fanciullo, L., Verstraete, L., et al. 2017, A&A
Hoang, T. 2017, ApJ, 847, 77
Hoang, T. 2019, ApJ, 876, 13
Hoang, T., Cho, J., & Lazarian, A. 2018, ApJ, 852, 129
Hoang, T., Draine, B. T., & Lazarian, A. 2010, ApJ, 715, 1462
Hoang, T., Lazarian, A., & Schlickeiser, R. 2012, ApJ, 747, 54
Hoang, T., & Tram, L. N. 2019, ApJ, 877, 36
Hoang, T., Tram, L. N., Lee, H., & Ahn, S.-H. 2019, Nature Astronomy, 3, 766
Hoang, T., Vinh, N. A., & Quynh Lan, N. 2016, ApJ, 824, 18
Ishibashi, W., & Fabian, A. C. 2015, MNRAS, 451, 93
Jones, A. P., Tielens, A. G. G. M., Hollenbach, D. J., & McKee, C. F. 1994, ApJ, 433, 797
Lazarian, A., & Hoang, T. 2007, ApJ, 669, L77
Micelotta, E. R., Matsuura, M., & Sarangi, A. 2018, Space Sci Rev, 1
Netzer, N., & Elitzur, M. 1993, ApJ, 410, 701
Nozawa, T., Kozasa, T., & Habe, A. 2006, ApJ, 648, 435
Purcell, E. M., & Spitzer, L. J. 1971, ApJ, 167, 31
Sankrit, R., Williams, B. J., Borkowski, K. J., et al. 2010, ApJ, 712, 1092
Sigmund, P. 1981, in Sputtering by Particle Bombardment I, ed. R. Behrisch (New York: Springer), 9
Tielens, A. G. G. M., McKee, C. F., Seab, C. G., & Hollenbach, D. J. 1994, ApJ, 431, 321
Tram, L. N., & Hoang, T. 2019, arXiv:1902.01921
Williams, B. J., Borkowski, K. J., Reynolds, S. P., et al. 2006, ApJ, 652, L33
Yan, H., Lazarian, A., & Draine, B. T. 2004, ApJ, 616, 895
Zhu, H., Slane, P., Raymond, J., & Tian, W. W. 2019, arXiv:1907.06213, arXiv:1907.06213