Grain Alignment and Disruption by Radiative Torques in Dense Molecular Clouds and Implication for Polarization Holes

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Abstract

Dust polarization induced by aligned grains is widely used to study magnetic fields in various astrophysical environments. However, the question of to what optical depth grain alignment still exists in a dense molecular cloud (MC) is unclear. In this paper, we derive analytical formulae for the minimum size of aligned grains (\(a_{\text{align}}\)) and rotational disruption (\(a_{\text{disr}}\)) by RAdiative Torques (RATs) as a function of the local physical parameters within MCs. We first find the analytical approximations for the radiation strength and mean wavelength of the attenuated radiation field in a dense MC with and without embedded stars, and then derive analytical formulae for \(a_{\text{align}}\) and \(a_{\text{disr}}\) as functions of the visual extinction \(A_V\) and gas density. We find that, within a starless core of density \(n_H \sim 10^4 \text{ cm}^{-3}\), grains of size \(a < 0.25 \mu\text{m}\) can be aligned at \(A_V \sim 5\) by RATs, whereas micron-sized grains can still be aligned at \(A_V \sim 50\). The increase in \(a_{\text{align}}\) with \(A_V\) can explain the presence of polarization holes observed toward starless cores. For MCs with an embedded protostar, the efficiency of both alignment and rotational disruption increases toward the protostar due to the increasing radiation strength. Such a disruption effect results in the decrease of the polarization degree with \(A_V\) or emission intensity, reproducing the popular polarization holes observed toward the location of protostars. Finally, we derive the formula for the maximum \(A_V\) where grain alignment still exists in a starless core, and we discuss its potential for constraining grain growth.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Astrophysical dust processes (99); Interstellar dust (836); Interstellar dust extinction (837); Dust continuum emission (412); Starlight polarization (1571); Interstellar magnetic fields (845)

1. Introduction

Interstellar dust is an essential component of the interstellar medium (ISM) and plays an important role in various astrophysical processes, including gas heating, star and planet formation, and grain-surface chemistry (for a review, see Draine (2003)). Dust polarization induced by grain alignment allows us to study magnetic fields in various astrophysical environments, from the diffuse interstellar medium (ISM) to dense molecular clouds (MCs) to protoplanetary disks. Magnetic fields are thought to play an important role in the process of star formation (Crutcher 2012). Therefore, observing dust polarization in star-forming regions is valuable in clarifying the role of magnetic fields in the process (Putnle & Fissel 2019). However, the question is to what optical depth in a dense MC grain alignment still exists, enabling a robust detection of the magnetic fields.

Observations of background starlight polarization in optical–near-infrared (NIR) are usually used to probe grain alignment in dark MCs (e.g., Whittet et al. 2008). Optical–NIR observations toward starless cores usually reveal the decrease of the polarization fraction with the visual extinction (Goodman et al. 1992; Whittet et al. 2008), which is known as the “polarization hole.” The polarization hole is also observed in far-IR/submm toward prestellar cores (Ward-Thompson et al. 2000; Crutcher et al. 2004). The exact origin of the polarization hole is still debated, but the popular explanations include the decrease of grain alignment toward the central region due to high gas density (Goodman et al. 1992, 1995) and the tangling of magnetic fields (Hull et al. 2014). Some observations of dust polarization from starless cores do indeed reveal the loss of grain alignment at a large visual extinction measured from the cloud surface of \(A_V > 20\) (Alves et al. 2014; Jones et al. 2015), whereas other observations (Wang et al. 2017; Putlle et al. 2019) show that grain alignment still exists at such large \(A_V\).

Moreover, NIR observations of background starlight polarization toward starless dark clouds reveal unusually large values of the peak wavelength (i.e., the wavelength of the maximum polarization), \(\lambda_{\text{max}} \sim 1–1.2 \mu\text{m}\) (Clemens et al. 2016), and \(\lambda_{\text{max}} \sim 0.6 – 0.9 \mu\text{m}\) (Wang et al. 2017). This suggests that the grain sizes are much larger than in the diffuse ISM, implying significant grain growth in dense MCs. Observations of polarized dust emission in far-IR/submm also reveal the existence of grain alignment in starless cores at large visual extinction of \(A_V \sim 20\). Moreover, observations of scattered light in NIR from dense clouds irradiated by a nearby star show evidence of micron-sized grains, which is known as core shines (Pagani et al. 2010; Steinacker et al. 2010; Juvela et al. 2012; Ysard et al. 2013). Theoretically, grain growth is expected to occur in dense MCs due to the accretion of gas species to the grain surface and grain–gas collisions (Hirashita & Li 2013). The remaining question is how such dust grains can still be aligned at such large values of \(A_V\).

The problem of grain alignment is one of the most long-standing questions in astrophysics. Since the discovery of starlight polarization in 1949 (Hall 1949; Hiltner 1949), which revealed the alignment of interstellar grains, many theories have been proposed (for a review, see Lazarian (2003)). The popular theory of grain alignment is Radiative Torque (RAT)
theory (Dolginov & Mitrofanov 1976; Draine & Weingartner 1997; Lazarian & Hoang 2007; Hoang & Lazarian 2008a), which is supported by numerous observations (for recent reviews, see Andersson et al. (2015) and Lazarian et al. (2015)). Numerical modeling of grain alignment by RATs in a starless dark cloud was presented in Cho & Lazarian (2005) and Bethell et al. (2007). Both studies only consider the alignment of grains induced by attenuated ISRF and assume a maximum visual extinction of $A_V = 10$. Therefore, their results cannot be directly applied to interpret observational data at larger $A_V$ in the era of high spatial resolution observations. Numerical simulations of dust polarization by aligned grains using the RAT alignment theory are being actively studied (Reissl et al. 2016). The main goal of this paper is to derive an analytical formula for the minimum size of aligned grains for dense MCs having much larger $A_V$.

Protostars are thought to form in the dense core of MCs. Polarimetric observations toward protostars by single dish and interferometric observations (e.g., Liu et al. 2013; Hull et al. 2014; Cox et al. 2018; see also Patte & Fissel 2019) usually reveal the existence of a “polarization hole,” which is described as the decrease of the polarization fraction with increasing column density or intensity of dust emission. Previous studies have usually appealed to two possible reasons to explain the polarization hole: the tangling of the magnetic field and the decrease of alignment efficiency toward the protostar (Hull et al. 2014). However, in the RAT alignment framework, one expects an increase of grain alignment efficiency toward the protostar due to the increasing incident radiation flux, resulting in an increase (instead of a decrease) of the polarization fraction with the peak intensity. Therefore, the underlying origin of the polarization hole toward protostars is difficult to reconcile in terms of grain alignment theory.

Recently, a new mechanism of grain destruction based on centrifugal force, the so-called Radiative Torque Disruption (RATD), has been introduced (Hoang et al. 2019; Hoang 2019). This mechanism is particularly efficient near protostars; for a review, see Hoang (2020). The RATD mechanism disrupts large grains into smaller ones, resulting in a decrease of the polarization fraction as the incident radiation field increases (Lee et al. 2020). As a result, we expect that the joint action of grain alignment and disruption by RATs could explain the observed polarization toward protostars. The second goal of this paper is to understand the origin of polarization holes via detailed modeling of grain alignment and rotational disruption by RATs in a dense MC with a central protostar.

The structure of the paper is as follows. In Section 2, we describe RATs and derive analytical formulae for the average RATs over a radiation spectrum. In Section 3, we present analytical formulae for grain alignment and disruption as functions of the visual extinction and local physical parameters. In Sections 4 and 5, we apply our analytical formulae for molecular clouds with and without embedded sources. Discussion of our results for polarization holes and grain growth is presented in Section 6. Our main findings are summarized in Section 7.

2. Radiative Torques of Irregular Grains

In this section, we describe RATs of irregular grains and derive analytical formulae for the RAT efficiency averaged over an arbitrary radiation spectrum, which will be used for alignment and disruption studies.

2.1. Radiative Torques

Let $u_\lambda$ be the spectral energy density and $\gamma$ be the anisotropy degree of the radiation field. The anisotropy degree is minimum of $\gamma = 0$ for isotropic radiation field and is maximum of $\gamma = 1$ for the unidirectional radiation field from a star. The energy density of the radiation field is then

$$u_{\text{rad}} = \int_0^\infty u_\lambda d\lambda.$$  \hfill (1)

To describe the strength of a radiation field, we introduce the dimensionless parameter $U = u_{\text{rad}} / u_{\text{ISRF}}$, with $u_{\text{ISRF}} = 8.64 \times 10^{-13} \text{erg cm}^{-3}$ being the energy density of the average interstellar radiation field (ISRF) in the solar neighborhood as given by Mathis et al. (1983, hereafter MMP83). Thus, the typical value for the ISRF in the solar neighborhood is $U = 1$. Throughout this paper, we use the CGS unit system, unless stated otherwise.

Let $a$ be the effective size of the grain which is defined as the radius of the sphere with the same volume as the irregular grain. Radiative torque (RAT) induced by the interaction of an anisotropic radiation field with the irregular grain is defined as

$$\Gamma_\lambda = \pi a^2 \gamma u_\lambda \left(\frac{\lambda}{2\pi}\right) G_\lambda,$$  \hfill (2)

where $G_\lambda$ is the RAT efficiency (Draine & Weingartner 1996; Lazarian & Hoang 2007).

The magnitude of RAT efficiency can be approximated by a power law,

$$G_\lambda = \alpha \left(\frac{\lambda}{a}\right)^{-\eta},$$  \hfill (3)

for $\lambda/a \gtrsim 0.1$, where $\alpha$ and $\eta$ are the constants that depend on the grain size, shape, and optical constants. Numerical calculations of RATs for several shapes of different optical constants in Lazarian & Hoang (2007) find slight differences in RATs among the realizations. They adopted the coefficients $\alpha = 0.4$, $\eta = 0$ for $a_{\text{trans}} < a < \lambda/0.1$, and $\alpha = 2.33$, $\eta = 3$ for $a < a_{\text{trans}}$, where $a_{\text{trans}} = \lambda/1.8$ denotes the transition size at which the RAT efficiency slope changes. Thus, the maximum RAT efficiency is $G_{\lambda,\text{max}} = \alpha$.

An extensive study for a large number of irregular shapes by Herranen et al. (2019) shows moderate difference in RATs for silicate, carbonaceous, and iron compositions. Moreover, the analytical formula (Equation (3)) is also in good agreement with their numerical calculations. Therefore, one can use Equation (3) for the different grain compositions and grain shapes, and the difference is of order unity.

The radiative torque averaged over the incident radiation spectrum of spectral energy density $u_\lambda$ is defined as

$$\Gamma_{\text{RAT}} = \pi a^2 \gamma u_{\text{rad}} \left(\frac{\lambda}{2\pi}\right) \bar{Q}_\lambda,$$ \hfill (4)

where

$$\bar{Q}_\lambda = \frac{\int_0^\infty \lambda Q_\lambda u_\lambda d\lambda}{\int_0^\infty \lambda u_\lambda d\lambda}, \quad \bar{\lambda} = \frac{\int_0^\infty \lambda u_\lambda d\lambda}{u_{\text{rad}}}$$ \hfill (5)

are the average RAT efficiency and the mean wavelength, respectively.
In general, one can numerically calculate the average RAT and average RAT efficiency using Equations (4) and (5) for an arbitrary radiation spectrum $u_\lambda$. To facilitate analysis of grain alignment from observations, in the following, we will derive analytical formulae for $Q_T$ and $\lambda$ for two popular radiation fields.

2.2. Average RAT over a Stellar Radiation Spectrum

For a radiation field produced by a star of temperature $T_\star$, the spectral energy density at distance $d$ from the star is

$$u_\lambda(T_\star) = \frac{4\pi R_\star^2 F_\lambda}{4\pi d^2 c} = \frac{\pi B_\lambda(T_\star)}{c} \left(\frac{R_\star}{d}\right)^2,$$

where $F_\lambda = \pi B_\lambda$ is the radiation flux from the stellar surface of radius $R_\star$, and $B_\lambda = (2hc^2/\lambda^5)(\exp(hc/\lambda kT_\star) - 1)^{-1}$ is the Planck function. For simplicity, we first disregard the reddening effect by intervening dust.

The total radiation energy density of the stellar radiation field becomes

$$u_{\text{rad}}(T_\star) = \frac{\int_0^\infty \pi B_\lambda(T_\star) d\lambda}{\int_0^\infty B_\lambda(T_\star) d\lambda} = \left(\frac{R_\star}{d}\right)^2 \frac{\sigma T_\star^4}{c},$$

where $\sigma = 2\pi^2 k^3/(15hc^2)$ is the Stefan–Boltzmann constant.

The mean wavelength of the stellar radiation field is given by

$$\bar{\lambda}(T_\star) = \frac{\int_0^\infty \lambda B_\lambda(T_\star) d\lambda}{\int_0^\infty B_\lambda(T_\star) d\lambda} = \left(2\pi k^3 \Gamma(3)\zeta(3)\right) \frac{1}{\sigma ch^2} \frac{1}{T_\star} \approx 0.53 \text{ cm K},$$

where $\Gamma$ and $\zeta$ are the Gamma and Riemann functions, and we have used the integral formula $\int_0^\infty x^{s-1}dx/(e^x - 1) = \Gamma(s)\zeta(s)$ for $s > 1$.

For small grains of $a < \bar{\lambda}/1.8$, plugging $Q_T$ from Equation (3) and $u_\lambda(T_\star)$ into Equation (5), one obtains the following after taking the integral:

$$\bar{Q}_T = \frac{2\pi\alpha k^{\eta+1}}{\sigma h^{\eta+2}c^{\eta+1}} \left(\zeta(3)\Gamma(3)2\pi k^3\right)^{\eta-1} \left(\frac{\bar{\lambda}}{a}\right)^{\eta-3},$$

plugging the RAT parameters of $\alpha = 2.33$ and $\eta = 3$ into Equation (9), one obtains

$$\bar{Q}_T \approx 6 \left(\frac{\bar{\lambda}}{a}\right)^{-3}.$$

Because the average RAT efficiency cannot exceed its maximum RAT efficiency, $Q_{T,\text{max}}$, the above equation is only valid for grains of size $a \lesssim Q_{T,\text{max}}/6^{1/3} \bar{\lambda} = \bar{\lambda}/2.5$. Large grains of $a > \bar{\lambda}/2.5$ then have $Q_T = Q_{T,\text{max}} = 0.4$. Let $\alpha_{\text{trans},\star} = \bar{\lambda}/2.5$ be the transition size of the RAT averaged over the stellar radiation spectrum.

2.3. Average RAT over the Interstellar Radiation Field

Following Mathis et al. (1983), the average ISRF in the solar neighborhood can be described by three stellar radiation fields,

$$u_{\lambda,\text{ISRF}} = \sum_i u_\lambda(T_{\lambda,i}) = \frac{4\pi}{c} \sum_i \sum_j W_j B_{\lambda,i}(T_{\lambda,i}),$$

where $T_{\lambda,i} = 7500, 4000, 3000$ K are the temperatures of the three stellar classes, and $W_i = 10^{-14}, 1.65 \times 10^{-13}, 4 \times 10^{-13}$ are the dilution factors. Above, we have ignored the contribution of ultraviolet (UV) component, which contributes $\sim 10\%$ of the total energy (see Draine & Weingartner 1996).

The RAT efficiency averaged over the radiation spectrum, $u_{\lambda,\text{ISRF}}$, is then written as

$$\Gamma_{\text{RAT}} = \sum_i \Gamma_{\text{RAT}}(T_{\lambda,i}),$$

where $\Gamma_{\text{RAT}}(T_{\lambda,i})$ is the average radiative torque over the stellar radiation of star temperature $T_{\lambda,i}$ given by

$$\Gamma_{\text{RAT}}(T_{\lambda,i}) = \pi a^2 \omega_{\text{rad},i} \left(\frac{\bar{\lambda}_i}{2\pi}\right) Q_T,$$

where $\bar{\lambda}_i$ and $Q_T$ are given by Equations (8) and (9), respectively, and

$$\omega_{\text{rad},i} = \frac{4W_i}{c} \sigma T_{\lambda,i}^4.$$

For $T_{\lambda,i} = 7500, 4000, 3000$ K, Equation (8) implies $\bar{\lambda}_i = \bar{\lambda}(T_{\lambda,i}) = 0.71, 1.32, 1.76 \mu m$, and $\omega_{\text{rad},i} = 2.39 \times 10^{-13} \times 10^{-13}, 2.45 \times 10^{-13}$ erg cm$^{-3}$. The total radiation energy is then $u_{\text{rad},\text{ISRF}} = \sum_i u_{\text{rad},i} = 8.04 \times 10^{-13}$ erg cm$^{-3}$, which is slightly smaller than $u_{\text{ISRF}} = 8.64 \times 10^{-13}$ erg cm$^{-3}$ when accounting for the UV component (Draine & Weingartner 1996).

The mean wavelength of the ISRF is calculated by Equation (5) with $u_\lambda$ replaced by $u_{\lambda,\text{ISRF}}$, yielding

$$\bar{\lambda} = \frac{\sum_i \bar{\lambda}_i \omega_{\text{rad},i}}{\sum_i \omega_{\text{rad},i}} = 0.53 \text{ cm K} \sum_i W_i T_{\lambda,i}^3 = 1.28 \mu m,$$

and the average torque can be rewritten as

$$\Gamma_{\text{RAT}} = \sum_i \Gamma_{\text{RAT}}(T_{\lambda,i}) = \pi a^2 \omega_{\text{rad},\text{ISRF}} \left(\frac{\bar{\lambda}}{2\pi}\right) \bar{Q}_T,$$

where

$$\bar{Q}_T = \frac{\sum_i \bar{\lambda}_i \omega_{\text{rad},i} \bar{Q}_T}{\bar{\lambda} \omega_{\text{rad},\text{ISRF}}}.$$

Equations (15) and (17) allow us to calculate the mean wavelength and the average RAT efficiency for an arbitrary radiation source consisting of different stars, such as star clusters.

For the ISRF, plugging $\bar{\lambda}_i$, $\omega_{\text{rad},i}$, and $\bar{Q}_T$ as given by Equation (10), into the above equation, one obtains

$$\bar{Q}_T \approx 8 \left(\frac{\bar{\lambda}}{a}\right)^{-3}.$$
for \( a < (Q_{\tau,\text{max}}/8)^{1/3} \lambda \approx \bar{\lambda}/2.7 \). Larger grains of size \( a > \bar{\lambda}/2.7 \) then have \( Q_{\tau} \approx Q_{\tau,\text{max}} = 0.4 \). Let \( a_{\text{trans,ISRF}} \equiv \bar{\lambda}/2.7 \) be the transition size of the RAT efficiency averaged over the ISRF.

Figure 1: Comparison of the average RAT efficiency obtained from analytical formulae with those from numerical calculations (Equation (5)) for a stellar radiation spectrum (upper panel) and the ISRF (lower panel). An analytical fit of \( Q_{\tau} \equiv 2(\lambda/a)^{-2.7} \) from HLM14 is also shown for comparison. Analytical formulae are in excellent agreement with numerical results for the stellar spectrum and the ISRF described by three stars. For the full ISRF, the analytical result is different from the numerical ones, due to the contribution of the enhanced UV spectrum.

3. Grain Alignment and Disruption by Radiative Torques

We now describe the basic theory of grain alignment and disruption, and then derive the general analytical formulae for the minimum size of aligned grains and disruption by RATs.

3.1. Theoretical Consideration

An anisotropic radiation field can align dust grains via the RAT mechanism; see Lazarian (2007) and Andersson et al. (2015) for reviews. For an ensemble of grains subject to only RATs, a fraction of grains is first spun up to suprathermal rotation and then driven to be aligned with the ambient magnetic fields (so-called B-RAT) or with the anisotropic radiation direction (i.e., k-RAT) at an attractor point with high angular momentum, usually referred to as high-J attractors. The high-J attractor corresponds to the maximum angular velocity induced by RATs. A large fraction of grains are driven to low-J attractors (Lazarian & Hoang 2007; Hoang & Lazarian 2009). In the presence of gas collisions, numerical simulations of grain alignment by RATs in Hoang & Lazarian (2008a, 2016) show that grains at the low-J attractor will be gradually transported to the high-J attractor after several gas damping times, establishing the stable efficient alignment. In dense MCs, the timescale for such a stable alignment is short compared to other dynamical timescales.

The existence of high-J attractors caused by RATs is expected for some grain shapes (Lazarian & Hoang 2007), and it becomes universal for grains with enhanced magnetic susceptibility via iron inclusions (Lazarian & Hoang 2008; Hoang & Lazarian 2016). This important finding is supported by simulations in Hoang & Lazarian (2016) for grains with various magnetic susceptibilities. Recent calculations of RATs for Gaussian random shapes by Herranen & Lazarian (2020) show a higher fraction of grain shapes with high-J attractors than previously expected by Herranen et al. (2019) for ordinary paramagnetic grains. Therefore, grain angular velocity induced by RATs is a key parameter for grain alignment (both B-RAT and k-RAT alignment) and rotational disruption.

3.2. Maximum Rotation Speed Induced by RATs

For a radiation source with constant luminosity considered in this paper, radiative torques \( \Gamma_{\text{RAT}} \) are constant, such that the grain angular velocity steadily increases over time. The equilibrium rotation can be achieved at (see..
for grains with $a > a_{\text{trans,ISRF}}$. Here, $\gamma_{-1} = \gamma/0.1$ is the anisotropy of the radiation field relative to the typical anisotropy of the diffuse interstellar radiation field of $\gamma \approx 0.1$ (e.g., Draine & Weingartner 1996).

### 3.3. Grain Alignment

Efficient grain alignment is achieved only when grains can rotate with an angular velocity greater than the thermal value, which is termed suprathermal rotation. The grain thermal angular velocity is

$$\omega_T = \left(\frac{kT_{\text{gas}}}{I_a}\right)^{1/2} = \left(\frac{15kT_{\text{gas}}}{8\pi\rho a^5}\right)^{1/2}$$

$$\approx 5.23 \times 10^4 \phi_0^{-1}\gamma_{-1}^{-1/2} \alpha_{-5}^{-5/2} T_{\text{gas}}^{1/2} \text{ rad s}^{-1}. \quad (25)$$

Using the suprathermal rotation threshold of $\omega_{\text{RAT}}(a_{\text{align}}) = 3\omega_T$ as in Hoang & Lazarian (2008b), one obtains the minimum size of aligned grains (hereafter alignment size) as follows:

$$a_{\text{align}} = \left(\frac{1.2m_H T_{\text{gas}}}{\gamma_{\text{rad}} \Lambda^2}\right)^{2/7} \left(\frac{15m_H k^2}{4\rho}\right)^{1/7} (1 + F_{\text{IR}})^{2/7}$$

$$\times \left(\frac{\Lambda}{1.2 \mu m}\right)^{4/7} (1 + F_{\text{IR}})^{2/7} \mu m, \quad (26)$$

which implies $a_{\text{align}} \sim 0.055 \mu m$ for a dense cloud of $n_H = 10^3 \text{ cm}^{-3}$ exposed to the local radiation field of $\gamma = 0.1$, $U = 1$, and $\Lambda = 1.2 \mu m$. In general, grain alignment by RATs depends on five local physical parameters of the gas ($n_H$, $T_{\text{gas}}$) and the radiation field at the cloud surface ($\gamma$, $U$, $\Lambda$). The alignment size increases with increasing $n_H$ and decreasing $U$.

In a very dense region with low radiation strength, the alignment size becomes large and can exceed $a_{\text{trans}}$. Therefore, the appropriate result is obtained by using $\omega_{\text{RAT}}$ from Equation (24), yielding

$$a_{\text{align}, \text{lg}} = \left(\frac{n_H T_{\text{gas}}}{\gamma_{\text{rad}} \Lambda^2}\right)^{2/7} \left(\frac{2160m_h k^2}{\rho}\right)$$

$$\times \left(\frac{\Lambda}{1.2 \mu m}\right)^{2} \mu m, \quad (27)$$

where $n_6 = n_H/(10^6 \text{ cm}^{-3})$ and $U_{-1} = U/10$. Note that grain alignment still occurs if $a_{\text{align}, \text{lg}} > a_{\text{trans}}$, because $\omega_{\text{RAT}}$ decreases with the grain size as $a^{-2.5}$, slower than the slope of $a^{-5}$ of $\omega_T$.

For molecular clouds, $F_{\text{IR}} \ll 1$. Thus, Equation (26) implies the minimum size of aligned grains by RATs when $n_H$, $T_{\text{gas}}$, and $T_d$ are known.

### 3.4. Grain Rotational Disruption

A rotating grain at angular velocity $\omega$ develops a centrifugal stress $S = \rho a^2 \omega^2/4$. When the grain rotation rate is sufficiently high, such that the tensile stress can exceed the tensile strength, $S_{\text{max}}$, the grain is instantaneously disrupted into fragments. This mechanism is termed Radiative Torque Disruption (RATD; Hoang et al. 2019). The critical angular velocity is obtained by...
setting $S = S_{\text{max}}$:

$$\omega_{\text{disr}} = \frac{2}{a} \left( \frac{S_{\text{max}}}{\rho} \right)^{1/2}$$

$$\simeq 3.65 \times 10^8 \frac{S_{\text{max}}}{a^5} \rho^{-1/2} S_{\text{max},7}^{1/2} \text{ rad s}^{-1}, \quad (28)$$

where $S_{\text{max},7} = S_{\text{max}}/10^7 \text{ erg cm}^{-3}$.

The tensile strength of interstellar dust is uncertain, depending on grain structure (compact versus composite) and composition (Hoang 2019). In dense MCs, grains are expected to be large and have composite structure as a result of the coagulation process. Numerical simulations for porous grain aggregates composed of constituent particles (so-called monomers) from Tatsuuma et al. (2019) find that the tensile strength decreases with increasing monomer radius and can be fitted with an analytical formula:

$$S_{\text{max}} \simeq 9.51 \times 10^4 \left( \frac{\gamma_{\text{sd}}}{0.1 \text{Jm}^{-2}} \right)$$

$$\times \left( \frac{r_0}{0.1 \mu m} \right)^{-1} \left( \frac{\phi}{0.1} \right)^{1.8} \text{ erg cm}^{-3}, \quad (29)$$

where $\gamma_{\text{sd}}$ 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 composite grains made of monomers of radius $r_0 = 0.1 \mu m$ with $\phi = 0.1$ and $\gamma_{\text{sd}} = 0.11 \text{ Jm}^{-2}$, Equation (29) implies $S_{\text{max}} \approx 10^5 \text{ erg cm}^{-3}$.

Comparing Equations (23) and (28), one can obtain the disruption grain size:

$$a_{\text{disr}} = \frac{0.8 n_H \sqrt{2 \pi m_H k T_{\text{gas}}}}{\gamma_{\text{rad}}} \left( \frac{S_{\text{max}}}{\rho} \right)^{1/4} (1 + F_{\text{IR}})^{1/2}$$

$$\simeq 1.7 \left( \frac{\gamma_{\text{rad}}}{n_i T_{\text{IR}}^{1/2}} \right)^{-1/2} \left( \frac{\lambda}{1.2 \mu m} \right) \rho^{-1/4} S_{\text{max},7}^{1/4}$$

$$\times (1 + F_{\text{IR}})^{1/2} \mu m, \quad (30)$$

which depends on the local gas properties, radiation field, and the grain tensile strength.

Due to the decrease of the rotation rate for $a > a_{\text{trans}}$ (see Equation (24)), the rotational disruption occurs only if $a_{\text{disr}} < a_{\text{trans.ISRF}}$. In this case, there exist a maximum size of grains that can still be disrupted by centrifugal stress (Hoang & Tram 2020).

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

$$\simeq 0.03 \left( \frac{\gamma_{\text{rad}}}{n_i T_{\text{IR}}^{1/2}} \right) \left( \frac{\lambda}{1.2 \mu m} \right) \rho^{1/2} S_{\text{max,7}}^{-1/2}$$

$$\times (1 + F_{\text{IR}})^{-1} \mu m. \quad (31)$$

Table 1 lists the physical parameters of the local environment used to calculate grain alignment and disruption by RATs, including the gas density ($n_H$), radiation strength ($U$), the color of the radiation field ($\lambda$), and the tensile strength of grain material ($S_{\text{max}}$).

4. Dense Clouds without Embedded Stars

We now apply the analytical formulae obtained in the previous section to study alignment and disruption of grains inside a dense MC without an embedded source. The case of a dense core with a central protostar will be considered in the next section.

4.1. Radiation Spectrum

Here, we assume that a dense MC is only illuminated by the ISRF with $u_{\lambda_{\text{ISRF}}}$, as described by Equation (11). The radiation field inside the MC includes the attenuated ISRF (aISRF) and far-IR emission from dust grains. The aISRF dominates the radiation spectrum for $\lambda < 20 \mu m$, whereas far-IR component dominates for $\lambda > 20 \mu m$ (Martin et al. 1983).

The spectral energy density of the aISRF, at a visual extinction $A_V$ measured from the surface of the cloud, can be described by radiative transfer as follows:

$$u_{\lambda}(A_V) = u_{\lambda}(A_V = 0) e^{-\tau(\lambda)}, \quad (32)$$

where $\tau(\lambda) = A_V/1.086$, and $u_{\lambda}(A_V = 0)$ is the spectral density at the cloud surface.

The wavelength dependence of the extinction (i.e., extinction curve), $A_{\lambda}/A_V$, is calculated from the parametric function of Cardelli et al. (1989). Here, we assume a ratio of total-to-selective extinction $R_V = A_V/(B - V) = 4$, with a reddening of $E(B - V) = A_B - A_V$. We chose $R_V = 4$, larger than the standard value of the diffuse ISM of 3.1 (Weingartner & Draine 2001), to account for the effect of grain growth in dense MCs.

The mean wavelength of the aISRF is computed by Equation (5) with $u_{\lambda}(A_V)$. The radiation density of the aISRF is $u_{\lambda_{\text{rad}}} = \int_0^\infty u_{\lambda}(A_V) d\lambda$. Practically, for numerical integration, we take $u_{\lambda_{\text{rad}}} = \int_{\lambda_1}^{\lambda_2} u_{\lambda}(A_V) d\lambda$, where the lower limit is $\lambda_1 = 0.091 \mu m$ (the Lyman limit) and the upper limit is $\lambda_2 = 20 \mu m$, above which RATs are negligible for grain alignment.

The spectral energy density of far-IR thermal dust emission, $u_{\lambda_{\text{dust}}}$, is approximately given by

$$\lambda u_{\lambda_{\text{dust}}} = \frac{4 \pi \lambda}{c} \sum_{i=1}^{3} W_i B_i(T_{d,i}), \quad (33)$$

where $T_{d,i} = 40, 24, 10 \text{ K}$, and $W_i = 2.5 \times 10^{-5}, 10^{-3}, 6 \times 10^{-3}$ (see Table 2, in Mathis et al. 1983).

The attenuated ISRF component is important for alignment of dust grains of sizes $a < 10 \mu m$. For very large grains (e.g., $a > 100 \mu m$), thermal emission from dust becomes important.
because their size is on the same order as the mean wavelength of strong RATs (see Equation (3)). In this paper, we are interested in the alignment and disruption of grains that are not very large (a ≲ 1 µm), so thermal dust emission is not important, due to their negligible RATs.

Figure 2 shows the spectral energy density at different visual extinctions, A_ν, inside an MC taken from MMP83, denoted by ν_u,MMP83 (gray lines), as well as its interpolation for the wavelengths of λ < 20 µm relevant for alignment of small grains of a ≲ 1 µm (blue lines). We also show the results obtained from the reddening law (Equation (32)) with ν_u(A_ν = 0) = ν_u,MMP83(A_ν = 0) with R_V = 4 (red lines). The results obtained from the reddening law are in good agreement with the numerical results, although the agreement is poorer for λ ~ 10–20 µm because the reddening law does not include the mid-IR emission as in MMP83. Moreover, we can see that UV–optical radiation rapidly decreases, but NIR radiation decreases slowly with A_ν. The reason is that the optical depth at NIR is much smaller than the visual extinction. For the optical–IR photons of λ ∼ 10 µm, the extinction can be described by a power law of A_ν/λ ∝ (λ/0.55 µm)^-β with a slope β ≈ 2. For A_ν = 10, one has A_ν,µm = 0.4A_ν and A_ν,µm = 0.14A_ν = 1.4. As a result, IR photons of λ ≥ 1 µm are weakly absorbed and can still be sufficient to align large grains at large visual extinction, as we show in the following section.

Figure 3 compares the average RAT efficiency as a function of the grain size for radiation fields in an MC. The analytical approximation (Equation (18)) fits the numerical calculations well.

When the spectral energy density is known, we calculate the radiation strength, U, and the mean wavelength, λ, for different A_ν. The upper and lower panels of Figure 4 show the decrease of U and the increase of λ with increasing A_ν, obtained using the reddened spectrum (solid line) and the spectrum from Mathis et al. (1983) (filled circles).

To describe the decrease of U with A_ν due to dust absorption, we introduce the analytical function,

$$ U = \frac{U_0}{1 + c_1A_\nu^{c_2}}. $$

where U_0 is the radiation strength at the cloud surface, and c_1, c_2 are the fitting parameters. For a giant MC at galactocentric distance D_G = 5 kpc studied in MMP83, U_0 ∼ 3 (see Figure 4), and U_0 = 1 for the ISRF in the solar neighborhood.

Assuming that the dust opacity at long wavelengths is κ_d ∝ λ^{-β}, the equilibrium temperature of grains at A_ν is

$$ T_d = \frac{T_d,0U^{1/(4+\beta)}}{16.4 K}, \text{ where } T_d,0 \text{ is the grain temperature at } U = 1. $$

Throughout this paper, we assume β = 2 and T_d,0 = 16.4 K for silicates in the ISM in the solar neighborhood (see Draine 2011). Chi-squared fitting of Equation (34) to the numerical values obtained from the reddening law yields best-fit parameters of (c_1, c_2) = (0.42, 1.22). Here, we use the Levenberg–Marquardt algorithm from the lmfit package in Python and assume the uncertainties of the data to be 10% of the numerical values. As shown in the upper panel of Figure 4, the function provides a good fit for A_ν < 20 but it overestimates the numerical result by 30% at A_ν = 50 (see dotted line versus solid line).

To describe the increase of the mean wavelength with A_ν due to reddening effect, we introduce an analytical function,

$$ \bar{\lambda} = \bar{\lambda}_0(1 + c_3A_\nu^{c_4}) $$

where \bar{\lambda}_0 = 1.3 µm for the diffuse ISRF at A_ν = 0, and c_3 and c_4 are the model parameters. Least chi-square fitting of the above equation to the numerical results yields (c_3, c_4) = (0.27, 0.76). As shown in the lower panel of Figure 4, the analytical expression fits the numerical result very well (see dotted line versus solid line). However, there exists some discrepancy at A_ν > 20 between the reddening-law and numerical results, arising from the fact that...
Plugging $U$ and $\bar{\lambda}$ from Equations (34) and (35) into (26), one obtains the analytical formula for alignment size:

$$a_{\text{align}} \simeq 0.055 \rho^{-1/3} \left( \frac{\gamma-U_0}{n_\text{H} T_1} \right)^{-2/7} \left( \frac{\lambda_0}{1.2 \, \mu m} \right)^{4/7} \times (1 + 0.24 A_V^{1.22}) \frac{2/2-2/(4+\beta) \gamma}{(1 + 0.27 A_V^{0.76})^{4/7} \mu m},$$

(37)

where $T_{0,1} = T_0/10$ K, and the IR damping term has been disregarded because $F_{\text{IR}} \ll 1$ for starless dense clouds (see Equation (22)).

If $a_{\text{align}} > a_{\text{trans}}$, only large grains can be aligned and the alignment size is given by Equation (27), yielding

$$a_{\text{align,}} \simeq 0.88 \rho^{-1} \left( \frac{\gamma-U_0}{n_\text{H} T_1} \right)^{-2} \left( \frac{\bar{\lambda}}{1.2 \, \mu m} \right)^{-2} \mu m.$$

(38)

Similarly, following Equation (30), the grain disruption size is then given by

$$a_{\text{disr}} \simeq 1.7 \left( \frac{\lambda_0}{1.2 \, \mu m} \right) \left( 1 + 0.27 A_V^{0.76} \right)^{-1/4} S_{\text{max},7}^{1/4} \times \left( \frac{\gamma-U_0}{n_\text{H} T_1} \right)^{-1/2} \left( 1 + 0.42 A_V^{1.22} \right)^{1/2} \mu m,$$

(39)

provided that $a_{\text{disr}} < a_{\text{trans,ISRF}} = \bar{\lambda}/2.7$. The RATD effect occurs only if $a_{\text{disr}} < a_{\text{trans,ISRF}}$, because grains larger than $a_{\text{trans,ISRF}}$ have $\omega_{\text{RAT}} < \omega_{\text{disr}}$ due to its decrease with $a$ (Equation (24)).

Equations (37)–(39) provide analytical results for the alignment and disruption sizes of grains at visual extinction $A_V$ inside the starless MC, which depend on four physical parameters of the gas ($n_\text{H}$) and the radiation field at the cloud surface ($\gamma$, $U_0$, $\lambda_0$), assuming gas–dust thermal equilibrium.

To check the validity of Equations (37)–(39), we numerically calculate the alignment size (disruption size) using $\omega_{\text{RAT}}$ from Equation (19), where $T_{\text{RAT}}$ is numerically computed using Equation (4), and apply the criteria for grain alignment (disruption) for the attenuated ISRF from MMP38. The obtained results are referred to as numerical results.

Figure 5 shows $a_{\text{align}}$ as a function of $A_V$ for analytical results (solid lines) versus numerical results (filled circles and dotted lines), assuming the different local gas density $n_\text{H}$. For numerical results, we assume the radiation field obtained from MMP83 and the reddened radiation field of the three-star approximation, which have $U_0 \approx 3$ and $\lambda_0 \approx 1.3 \, \mu m$. Our analytical results are in excellent agreement with numerical results. The alignment size increases gradually with $A_V$ and $n_\text{H}$. For $n_\text{H} = 10^4 \, \text{cm}^{-3}$, standard grains (size $< 0.3 \, \mu m$) can be aligned up to $A_V \approx 10$ and only large grains can be aligned at $A_V > 20$ (see blue lines). For denser clouds with $n_\text{H} \sim 10^5 \, \text{cm}^{-3}$, only large grains of $a > 0.5 \, \mu m$ can be aligned at $A_V > 10$ and micron-sized grains can be aligned up to $A_V \approx 50$ (see orange line).

Our above results are calculated for a dense cloud of constant density. Our theoretical formulæ could be easily adapted to a starless core that follows a Plummer/Bonnor–Ebert density profile.

**Figure 4.** Radiation strength (upper panel) and the mean wavelength (lower panel) as functions of the visual extinction measured from the surface, $A_V$. Circle symbols show numerical calculations. Solid and dotted lines show analytical results using the reddening law and best fit to these. In the lower panel, the mean wavelength of far-IR thermal dust (Equation (33)) is also shown for comparison; however, it is not important for alignment and disruption of sub- and micron-sized grains, because $\bar{\lambda} \gg a$.

**Figure 5.** Disruption size (alignment size) as a function of $A_V$ for analytical results (solid lines) versus numerical results (filled circles and dotted lines), assuming the different local gas density $n_\text{H}$. For numerical results, we assume the radiation field obtained from MMP83 and the reddened radiation field of the three-star approximation, which have $U_0 \approx 3$ and $\lambda_0 \approx 1.3 \, \mu m$. Our analytical results are in excellent agreement with numerical results. The alignment size increases gradually with $A_V$ and $n_\text{H}$. For $n_\text{H} = 10^4 \, \text{cm}^{-3}$, standard grains (size $< 0.3 \, \mu m$) can be aligned up to $A_V \approx 10$ and only large grains can be aligned at $A_V > 20$ (see blue lines). For denser clouds with $n_\text{H} \sim 10^5 \, \text{cm}^{-3}$, only large grains of $a > 0.5 \, \mu m$ can be aligned at $A_V > 10$ and micron-sized grains can be aligned up to $A_V \approx 50$ (see orange line).

**4.2. Alignment and Disruption Size**

Assuming gas–dust thermal equilibrium, the gas temperature can also be described by a power law,

$$T_{\text{gas}} = \frac{T_0}{(1 + c_1 A_V^{1/3})^{1/(4+\beta)}},$$

(36)

where $T_0 = T_{0,1} 10^{1/(4+\beta)}$ K is the gas temperature at $A_V = 0$. This implies a slow decrease of $T_{\text{gas}}$ with $A_V$ due to its dependence as a slope of $1/(4+\beta)$. The above gas–dust equilibrium assumption is valid in dense clouds where gas heating is dominated by dust collisions (e.g., Forbrich et al. 2014). Thus, it becomes invalid in the outer layer of the cloud where gas heating by UV photons and cosmic rays is important.
5. Dense Clouds with an Embedded Protostar

We move on to study grain alignment and disruption via internal radiation for dense clouds with embedded sources (e.g., protostars).

5.1. Radiation Field and Density Profile

Let us consider now a dense cloud with an embedded protostar of bolometric luminosity $L_*$ and effective temperature $T_*$. The mean wavelength of the stellar radiation spectrum, $\lambda_*$, is given by Equation (8).

Due to the extinction by intervening dust, the radiation strength of the attenuated radiation field at radial distance $r$ from the central protostar is given by

$$U(r) = \frac{\int_0^\infty u_\lambda(T_\lambda) e^{-\tau_\lambda} d\lambda}{u_{ISRF}},$$

where $u_\lambda(T_\lambda) = L_\lambda/(4\pi r^2c)$ is the spectral energy density in the absence of dust extinction and $\tau_\lambda$ is the optical depth of intervening dust.

Following Equation (8), the mean wavelength of the attenuated stellar spectrum is

$$\bar{\lambda} = \frac{\int_0^\infty \lambda u_\lambda(T_\lambda) e^{-\tau_\lambda} d\lambda}{\int_0^\infty u_\lambda(T_\lambda) e^{-\tau_\lambda} d\lambda}.\quad (41)$$

Practically, for numerical integration, we adopt a lower limit of $\lambda_1 = 0.091 \mu m$ (Lyman limit) and an upper limit of $\lambda_2 = 20 \mu m$ for Equations (40) and (41).

The protostellar core is assumed to consist of a central region of radius $r_{in}$ and the envelope. The radial gas density of the protostellar core can be approximately described by a power law:

$$n_H(r) = \begin{cases} n_{in} & \text{for } r \leq r_{in}, \\ n_{in} \left(\frac{r}{r_{in}}\right)^p & \text{for } r > r_{in}, \end{cases}\quad (42)$$

where $n_{in}$ is the gas number density of the central region and $p > 0$ is the power slope that describes the rapid decrease of the gas density with radial distance in the envelope. The typical slope is $p = 3/2$ in the inner envelope and reaches $p = 2$ in the outer envelope (Whitworth & Ward-Thompson 2001).

The central region has a column density of $N_H(r \leq r_{in}) = n_{in}r$. The column density of gas obscuring the protostar at a distance $r > r_{in}$ is given by

$$N_H(r > r_{in}) = \int_0^r n_H(r') dr'$$

$$= n_{in}r_{in} + \frac{n_{in}r_{in}}{p-1} \left[ 1 - \left(\frac{r}{r_{in}}\right)^{p+1} \right],$$

$$\simeq 1.5 \times 10^{22} n_{in} g_{r_{in}} 10^{21} \text{cm}^{-2},$$

where $n_{in} = n_H/10^3 \text{cm}^{-3}$ and $r_{in} = r_{in}/100 \text{au}$.

The wavelength-dependent dust extinction is described by $A_{\nu,*} = 1.086\nu(\lambda)$, and the visual extinction of the central protostar is related to the column density as $A_{\nu,*}/N_H = R_{\nu}/(5.8 \times 10^{21} \text{cm}^{-2})$ (see Draine 2011). Thus, the central region has a total visual extinction of

$$A_{\nu,*} \approx \frac{N_H(r = r_{in})}{5.8 \times 10^{21} \text{cm}^{-2}} R_{\nu} \simeq 10.3 n_{in} g_{r_{in}} 10^{21} \text{cm}^{-2}.\quad (44)$$

The visual extinction measured from the protostar to a radial distance $r$ in the envelope is then given by

$$A_{\nu,*}(r) = \left(\frac{N_H(r)}{5.8 \times 10^{21} \text{cm}^{-2}} R_{\nu}\right)$$

$$= A_{\nu,c} \left(1 + \frac{1}{p-1} \left[ 1 - \left(\frac{r}{r_{in}}\right)^{p+1} \right] \right),\quad (45)$$

and $A_{\nu,c}(r) = A_{\nu,c}(r/r_{in})$ for $r \leq r_{in}$.

The total dust extinction of the central star is $A_{\nu,*}(r > r_{in}) \approx A_{\nu,c}(p)/(p-1)$. This implies $A_{\nu,*}(r > r_{in}) = 2A_{\nu,c}$ and $3A_{\nu,c}$ for a steep density slope of $p = 2$ and $p = 3/2$, respectively.

The visual extinction measured from the cloud surface inward, $A_{\nu,c}$, can be calculated using the visual extinction from the protostar, $A_{\nu,*}$, as follows

$$A_{\nu}(r) = A_{\nu,*}(r > r_{in}) - A_{\nu,*}(r)$$

$$= \frac{p A_{\nu, c}}{p-1} - A_{\nu,*}(r),\quad (46)$$

which yields $A_{\nu}(r) = \frac{A_{\nu,*}}{p-1} (r/r_{in})^p + 1$ for $r > r_{in}$ and $A_{\nu}(r) = A_{\nu,c}(p)/(p-1) - (r/r_{in})$ for $r \leq r_{in}$.

Due to dust extinction, the intensity of the stellar radiation field decreases but its mean wavelength increases with visual extinction $A_{\nu,*}$. Following Section 4, the radiation strength at $A_{\nu,*}$ from the source is described by

$$U = \frac{U_*}{1 + c_1 A_{\nu,*}^2} = \frac{U_{in}}{1 + c_1 A_{\nu,c}} \left(\frac{r}{r_{in}}\right)^{-2},\quad (47)$$

where $U_*$ is the radiation strength at radial distance $r$ in the absence of dust extinction, $U_{in} = L_*/(4\pi r_{in}^2 c_{ISRF})$ is the radiation strength at $r = r_{in}$ and $c_1$ and $c_2$ are the fitting parameters. The mean wavelength of the attenuated stellar
spectrum is
\[ \bar{\lambda} = \bar{\lambda}_* (1 + c_3 A_{V_\star}^{c_4}), \] (48)
where \( c_3 \) and \( c_4 \) are the fitting parameters.

As in the previous section, we perform a least chi-square fitting of \( U/U_\ast \) (using Equation (47)) and \( \bar{\lambda}/\bar{\lambda}_* \) (using Equation (48)) to their numerical values in order to obtain the best-fit parameters. The best-fit parameters and their uncertainties are shown in Table 2.

Assuming gas–dust thermal equilibrium and using Equation (34), one obtains the gas temperature as a power-law

\[ T_{\text{gas}} = T_m \left( \frac{r}{r_{\text{in}}} \right)^{-q} (1 + c_3 A_{V_\star}^{c_4})^{-q/2}, \] (49)

where \( T_m = T_d U^{1/(4+\beta)} \) K is the grain temperature at \( r_{\text{in}} \) and \( q = 2/(4 + \beta) \). The assumption of gas–dust thermal equilibrium for the protostellar core is invalid in the photodissociation region (PDR) around high-mass protostars where gas heating by photoelectric effect is important. However, this PDR region with \( A_{V_\star} \lesssim 3 \) is negligible compared to the total extinction of the central region \( A_{V_\star} \) (Equation (44)).

Figure 6 shows the variation of \( U/U_\ast \) and \( \bar{\lambda}/\bar{\lambda}_* \) with \( A_{V_\star} \), obtained from numerical calculations using Equations (40) and (41) for the different stellar temperatures. The best-fit models obtained from Equations (47) and (48) with the best-fit parameters listed in Table 2 are also shown by the solid lines, for comparison. The analytical fit is very good for \( A_{V_\star} < 30 \) and decreases for larger \( A_{V_\star} \), but the difference is less than 15% at \( A_{V_\star} = 50 \). The variation of the normalized strength and mean wavelength is, in general, steeper for larger \( T_* \); the reason is that a higher \( T_* \) induces faster attenuation of the stellar radiation due to there being more UV photons, which are more heavily extincted, resulting in a steeper variation of \( U \) and \( \bar{\lambda} \) on \( A_{V_\star} \).

5.2. Alignment and Disruption

The alignment and disruption size of grains by RATs induced by the attenuated protostellar radiation can be obtained using Equations (26) and (30). Because these equations are derived using the RAT efficiency averaged over the ISRF, which is larger than that for the stellar radiation field by a factor of 8/6 (Equations (18) versus (10)), we will add the factor of \( 8/6 \) to the \( \gamma_{\text{rad}} \) term in these equations for the stellar radiation field.

Thus, plugging \( n_H \) (Equation (42)), \( U \) (Equation (47)), \( \bar{\lambda} \) (Equation (48)), and \( T_{\text{gas}} \) (Equation (49)) into Equation (26), one obtains the alignment size at visual extinction \( A_{V_\star} \) from the protostar,

\[ a_{\text{align}} = \left( \frac{n_H T_{\text{gas}}}{(6/8) \gamma_{\text{rad}} \bar{\lambda}^2} \right)^{2/\gamma} \left( \frac{15 m_H k^2}{4 \rho} \right)^{1/\gamma} (1 + F_{\text{IR}})^2/\gamma \]
\[ \simeq 0.031 \bar{\lambda}^{1-1/\gamma} \left( \frac{U_{\infty,6}}{n_{\infty,8}^2 r_{1/2}^{3/2}} \right)^{2/\gamma} (1 + c_3 A_{V_\star}^{c_4})^{2/\gamma} \times \left( \frac{r}{r_{\text{in}}} \right)^{(2-\gamma)/\gamma} (1 + F_{\text{IR}})^2/\gamma \mu m, \] (50)

where \( \gamma = 1 \) is adopted for the unidirectional field from the protostar, and \( U_{\infty,6} = U_{\infty}/10^6 \).

Modifying Equation (30) for the average RAT efficiency of the stellar radiation implies the disruption size at visual extinction \( A_{V_\star} \):

\[ a_{\text{disr}} = \left( \frac{0.8 n_H \sqrt{2 \pi m_H k T_{\text{gas}}}}{(6/8) \gamma_{\text{rad}} \bar{\lambda}^2} \right)^{1/4} \left( \frac{S_{\text{max}}}{\rho} \right)^{1/4} (1 + F_{\text{IR}})^{1/4} \]
\[ \simeq 0.35 \bar{\lambda}^{1-1/4} S_{\text{max}}^{1/4} \left( \frac{U_{\infty,6}}{n_{\infty,8}^2 r_{1/2}^{3/2}} \right)^{1/4} (1 + c_3 A_{V_\star}^{c_4}) \times \left( \frac{r_{\text{in}}}{r} \right)^{(2-\gamma)/2} (1 + F_{\text{IR}})^{1/2} \mu m. \] (51)

The RATD effect occurs only if \( a_{\text{disr}} < a_{\text{trans}, \gamma} = \bar{\lambda}/2.5 \) because grains larger than \( a_{\text{trans}, \gamma} \) have \( \omega_{\text{RAT}} \) decreasing with \( a \) (Equation (24)). The maximum size for RATD is given by Equation (31),

\[ a_{\text{disr}, \gamma} = \left( \frac{(6/8) \gamma_{\text{rad}} \bar{\lambda}}{16 \pi (6/8) \gamma_{\text{rad}} \bar{\lambda}} \right)^{1/2} \frac{S_{\text{max}}}{\rho} (1 + F_{\text{IR}})^{-1} \]
\[ \simeq 0.7 \bar{\lambda}^{1/2} S_{\text{max}}^{1/2} \left( \frac{U_{\infty,6}}{n_{\infty,8}^2 r_{1/2}^{3/2}} \right) (1 + c_3 A_{V_\star}^{c_4}) \times \left( \frac{r_{\text{in}}}{r} \right)^{(2-\gamma)/2} (1 + F_{\text{IR}})^{-1} \mu m. \] (52)

For the central region of \( r < r_{\text{in}} \), the gas density is \( n_H = n_{\infty} \). Thus, the alignment and disruption size are described by Equations (50) and (51) by setting \( p = 0 \). Due to the high gas density of the protostellar core, Equation (22) implies \( F_{\text{IR}} \ll 1 \). Thus, one can ignore the 1 + \( F_{\text{IR}} \) term in the above equations.
For our numerical calculations, we assume $n_{in} = 10^4 \text{ cm}^{-3}$, $r_{in} = 30 \text{ au}$ for low-mass protostars (see, e.g., Visser et al. 2012) and $n_{in} = 10^7 \text{ cm}^{-3}$, $r_{in} = 500 \text{ au}$ for high-mass protostars (see Bisschop et al. 2007). The luminosity of the protostars is varied. With these parameters, the central region has a visual extinction of $A_{V,c} \approx 31$ and $A_{V,c} \approx 52$ for the low-mass and high-mass protostars, respectively, assuming $R_V = 4$. We consider the spherical protostellar core from $r = r_{min} = 0.01r_{in}$ to $r_{max} \gg r_{in}$, where $r_{max}$ is chosen such that $n_{ih}(r_{max}) \approx 100 \text{ cm}^{-3}$ for $p = 2$. The calculations for $a_{align}$ and $a_{diss}$ begin from $r = r_{min}$ outward. For each value of $r$, we calculate the alignment and disruption size using analytical formulae (Equations (50)–(52)), which are referred to as analytical results.

To check the validity of our analytical results, we will numerically calculate the alignment size (disruption size) using $\omega_{RAT}$ from Equation (19), where $T_{RAT}$ is numerically computed using Equation (4), and apply the criteria for grain alignment (disruption) for the stellar radiation using the reddening law (Equation (40)). The obtained results are referred to as numerical results. Note that, for numerical calculations, the IR damping is considered (see analytical results).

Figure 7 shows the variation of $a_{align}$ obtained from our analytical formula with numerical results as a function of $A_{V,*}$ for low-mass protostars of different luminosity, assuming the typical density slope of $p = 3/2$ (upper panel) and $p = 2$ (lower panel). First, one can see that analytical results (solid lines) are in good agreement with numerical results (filled circles). Second, the alignment size is lower for more luminous sources. For the slope $p = 1/2$, at large $A_{V,*} > A_{V,c}$ (i.e., in the protostellar envelope), the alignment size decreases gradually with decreasing $A_{V,*}$ (increasing $A_V$), and only large grains of $a > a_{align} \sim 0.15 \mu \text{m}$ can be aligned.
because of the rapid increase in the gas density as $1/r^2$. When entering the central region of $A_{V,*} < A_{V,c}$ with constant $n_H$, the alignment size decreases rapidly with $A_{V,*}$, due to the increase of the radiation intensity. For the slope $p = 2$, the alignment size changes slightly in the envelope of $A_{V,*} > A_{V,c}$, because the ratio $U/n_H$ is constant due to their similar dependence on the radial distance as $1/r^2$. When entering the central region of constant density, the alignment size decreases rapidly due to the increase of $\mu U/n_H$, similar to the results shown in the upper panel.

Figure 8 shows results similar to those in Figure 7, but for high-mass protostars. As is the case with low-mass protostars, only large grains of $a > 0.1$ $\mu$m can be aligned in the envelope, but small grains could be aligned in the central region, due to stronger radiation. Good agreement between analytical and numerical results is seen for $A_{V,*} < 40$, and the difference is larger, up to $20\%$ for $A_{V,*} > 40$. This is because the analytical fit of the RAT efficiency and the mean wavelength is not good for high stellar temperatures at very large $A_{V,*}$ (see Figure 3).

Figure 9 shows the variation of $a_{\text{disr}}$ and $a_{\text{disr, max}}$ obtained from our analytical formulae (solid lines) with numerical results (dashed lines) as functions of $A_{V,*}$ for low-mass protostars with $p = 3/2$ (upper panel) and $p = 2$ (lower panel), assuming the typical tense strength of $S_{\text{max}} = 10^5$ erg cm$^{-3}$ for large composite grains of $a > 0.1$ $\mu$m (see Equation (29)). Grain disruption mostly occurs within the central region of $A_{V,*} < A_{V,c}$.

Figure 10 shows similar results similar to those in Figure 9, but for high-mass protostars. For the case of $L = 10^5 L_\odot$, the disruption zone can extend well beyond the central region and into the envelope.
we study the rotational disruption of grains in dense MCs using the newly discovered RATD effect (Hoang et al. 2019; Hoang 2019). We find that, toward the protostar, both the minimum size of grain alignment and disruption decrease; these changes correspond to the increase in efficiency of grain alignment and disruption. We test our analytical formulae with numerical calculations and obtain good agreement for dense MCs. Therefore, the obtained formulae can be used to predict grain alignment and disruption, as well as to interpret polarimetric observations. We note that the RAT alignment theory was incorporated into the POLARIS code (Reissl et al. 2016), which enables numerical simulations of synthetic dust polarization. A recent numerical study by Seifried et al. (2019) found that small grains of \( a < 0.1 \mu m \) can still be aligned in dense clouds of \( n_H \sim 10^3 \sim 10^4 \text{ cm}^{-3} \) due to ISRF, which is consistent with our analytical results.

6.2. Polarization Holes in Starless Dense Cores

Polarization holes, i.e., decreases of the polarization fraction with visual extinction (AV) or column density (N_H), were frequently observed toward starless dense cores (e.g., Alves et al. 2014). Such a decrease is described by a power law of \( P_{\text{pol}}/P_{\text{pol}} \propto A_V^{-\xi} \) for polarization of background starlight and \( P_{\text{pol}} \propto L_{\text{em}}^{-\xi/2} \) for the polarization of thermal dust emission where the power slope \( \xi \sim 0 \sim 1 \). Here, for simplicity, we consider the long wavelength with optically thin and ISRF, although it may not be valid for particular objects (see Pattle et al. 2019).

The minimum size of aligned grains \( a_{\text{align}} \) in starless clouds increases with increasing \( AV \), as given by Equation (37) and shown in Figure (5). Therefore, if the maximum grain size is constant within the cloud, the degree of dust polarization by dichroic extinction is expected to decrease with increasing \( AV \) with the slope of \( \xi \sim 1 \). This successfully reproduces the popular polarization hole in starless cores. In particular, when the minimum size of aligned grains is larger than the maximum size of grains, i.e., \( a_{\text{align}} > a_{\text{max}} \), the slope is steep, with \( \xi = 1 \), as predicted in Cho & Lazarian (2005) and Whittet et al. (2008). In this case, it is considered an “ideal” polarization hole, as previously observed in starless cores (e.g., Alves et al. 2014; Jones et al. 2015; Liu et al. 2019).

We now estimate the maximum visual extinction that grain alignment still exists in a starless core for a given maximum size of grains, \( a_{\text{max}} \). For \( AV > 1 \), Equation (37) yields

\[
a_{\text{align}} \approx 0.02 \rho^{-1/3} A_V^{5/7} \left( \frac{\gamma - 1 U_0}{n T_1} \right)^{2/7} \left( \frac{\bar{\lambda}_0}{1.2 \mu m} \right)^{4/7} \mu m. \tag{53}
\]

Therefore, the ideal polarization hole is produced if \( a_{\text{align}} > a_{\text{max}} \) which implies

\[
A_{V, \text{max}} \approx 32.7 \rho^{1/5} 0.07 \left( \frac{a_{\text{max}}}{0.25 \mu m} \right)^{7/5} \frac{\left( \gamma - 1 U_0 \right)^{2/5}}{n T_1} \left( \frac{\bar{\lambda}_0}{1.2 \mu m} \right)^{4/5}. \tag{54}
\]

For dense cores with anisotropy of \( \gamma = 0.3 \) (Bethell et al. 2007) and gas density of \( n_H = 10^4, 10^5, 10^6 \text{ cm}^{-3} \), the above equation implies \( A_{V, \text{max}} \approx 20.3, 8.2, 3.3 \) for the standard maximum size of interstellar dust with \( a_{\text{max}} = 0.25 \mu m \). For a larger value of

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Figure 10. Same as Figure 9, but for high-mass protostars with a temperature \( T_c = 10^4 \text{ K} \). RATD mainly occurs within the central region, but it can occur in the envelope for the case of \( L = 10^5 L_\odot \).
When the grain temperature can be inferred from the spectral energy density (SED) observations, one can also check whether large grains can be aligned in the region. Using Equation (26), one obtains the minimum strength of the local radiation field required for alignment of largest grains by setting $a_{\text{align}} = a_{\text{max}}$, yielding

$$U_{\text{min}} = 3.8 \times 10^{-2} \gamma^{-2} n_6 T_1 \left( \frac{a_{\text{max}}}{1 \mu m} \right)^{-7/6} \left( \frac{\lambda_0}{1.2 \mu m} \right)^2,$$

converting to the minimum grain temperature,

$$T_{d,\text{min}} = T_{d,0} U_{\text{min}}^{1/6} = 9.5 \gamma^{-1/6} (n_6 T_1)^{1/6} \frac{a_{\text{max}}}{1 \mu m}^{-7/12} \left( \frac{\lambda_0}{1.2 \mu m} \right)^{1/3} K,$$

where $T_{d,0} = 16.4 K$ is assumed for the dust silicate temperature at the cloud surface in the solar neighborhood with $U_0 = 1$ (see Draine 2011).

The minimum radiation strength (temperature) decreases with increasing maximum grain size and decreasing gas density. In a very dense region of $n_1 \gtrsim 10^6$ cm$^{-3}$, the radiation field must be sufficiently strong so that grains can be heated to $T_d \gtrsim 9.5 K$ in order to align micron-sized grains.

### 6.3. Polarization Holes toward Dense Clouds with an Embedded Source

Polarization of dust emission in far-IR/submm (Hildebrand et al. 2000) is uniquely helpful when probing grain alignment in the densest part of an MC, thanks to the powerful polarimetric capability of the JCMT/POL-2, SOFIA/HAWC +, and ALMA. Numerous observations of dust polarization toward protostars show the decrease of polarization fraction with the intensity as $F_{\text{min}} \propto I_{\text{min}}^{-\xi}$ with different slopes $\xi$ for the different clouds. For instance, a value of $\approx 0.5-0.8$ is reported for low-mass (Soam et al. 2019; Coudé et al. 2019; Kwon et al. 2019) and high-mass protostars (Liu et al. 2020). Pattle et al. (2019) obtained a slope of $\xi \approx 0.34$ for the Ophiuchus A cloud, which is asymmetrically illuminated by a B star S1.

#### 6.3.1. Effects of Internal Stellar Radiation

Our modeling of grain alignment and disruption of grains in a protostellar core shows that, under the effect of the stellar radiation field, the alignment size $a_{\text{align}}$ first changes slowly in the envelope and then decreases rapidly when entering the central region around the protostar, due to the increase of the radiation flux and constant gas density (see Figures 7 and 8). Therefore, if the grain size distribution is constant, the polarization of thermal dust emission would increase toward the central protostar, producing a flat slope of $\xi = 0$. We also found that large grains in the central region are rotationally disrupted by RATs into smaller fragments (see Figures 9 and 10). The removal of the largest grains by RATs is predicted to reduce the polarization at long wavelengths (Lee et al. 2020), such that one expects an intermediate slope of $0 < \xi < 1$ toward the central protostar.

It is worth mentioning that Pillai et al. (2020) report a slope of $\xi = 0.55$ for the region with embedded stars. Their detailed modeling of polarized emission using the RAT theory could approximately reproduce the observed slope for the lower range of $I_{\text{em}}$. However, their predicted polarization degree for the central region tends to increase with intensity for $\log_{10} I_{\text{em}} > 0.5$ Jy/pixel, which is inconsistent with the observed trend (see their Figure 4(b)). We expect that such a discrepancy would be resolved if the RATD effect were taken into account.

#### 6.3.2. Effects of External ISRF

Our results for protostellar core ignore the effect of the attenuated ISRF, because we focused on the central region and the envelope with high density in which grain alignment by ISRF is already lost (see Figure 5). We found that the size of grains aligned by stellar radiation increases outward (toward the cloud surface; see, e.g., Figure 7). However, in the outer layer of the protostellar envelope where ISRF can induce grain alignment, the size is expected to increase inward. Therefore, there exists a range of $A_V$ where grain alignment by both ISRF and stellar radiation is completely lost (i.e., $a_{\text{align}} > a_{\text{max}}$), producing an ideal polarization hole with slope of $\xi = 1$.

Let $A_{V,\text{loss}}$ be the visual extinction from the surface at which grain alignment by RATs begins to completely cease, which is defined as $a_{\text{align}} = a_{\text{max}}$. We first estimate the minimum visual extinction measured from the protostar, $A_{V,*,\text{loss}}$, for alignment loss by stellar radiation by setting $a_{\text{align}}$ from Equation (50) to $a_{\text{max}}$. For $A_{V,*} > 1$, we have

$$A_{V,*,\text{loss}} \propto 32.3 \left( \frac{a_{\text{max}}}{1 \mu m} \right) \frac{\lambda_0}{1.2 \mu m} \left( \frac{R_{\text{loss}}}{r_3} \right)^{-2(2-p-\xi)/\xi} \left( \frac{U_{\text{los},6}}{n_{\text{os},8} T_{\text{los},2}} \right)^{2/7},$$

where the relationship between $r_{\text{los}}/r_3$ and $A_{V,*,\text{loss}}$ is given by Equation (45). The value of $A_{V,*,\text{loss}}$ is then the root of Equation (57) for a given $a_{\text{max}}$. Finally, the visual extinction from the surface, $A_{V,\text{loss}}$, is obtained from $A_{V,*,\text{loss}}$ through Equation (46).

Similarly, we can estimate the minimum visual extinction from the surface ($A_{V,\text{loss}}$) above which grain alignment by the ambient ISRF is completely lost, which is given in Equation (54). The gas density and its relationship with the visual extinction are given by Equations (42) and (46), respectively.

Figure 11 shows the dependence of $A_{V,\text{loss}}$ on the maximum grain size $a_{\text{max}}$ for grain alignment induced by ISRF (dashed line) and by radiation from the central protostar with different luminosity for low-mass (upper panel) and high-mass (lower panel) protostars. The loss of grain alignment by ISRF begins at larger $A_V$ (deeper into the cloud) when $a_{\text{max}}$ increases, as expected, but the alignment loss occurs at $A_V > 12.5$ and 25 for low-mass and high-mass protostars, respectively, assuming $a_{\text{max}} \sim 1 \mu m$. On the other hand, the loss of grain alignment by stellar radiation occurs at smaller $A_V$ (closer to the surface) for larger $a_{\text{max}}$. There exists a range of $A_V$, which is indicated by a shaded region in the figure, where grain alignment by both ISRF and internal stellar radiation is completely lost. The space of alignment loss shrinks as the luminosity of the protostar or the maximum grain size increase.
Our above discussion disregarded the effect of magnetic field fluctuations and turbulent structures, which are usually invoked to explain the polarization hole (e.g., Hull et al. 2014; Pattle & Fissel 2019). Identifying the primary process responsible for the polarization hole requires detailed numerical modeling of dust polarization with grain alignment and disruption for realistic three-dimensional magnetic fields combined with observational data.

6.4. Constraining Grain Sizes in Dense Clouds

Grains in dense MCs are expected to be larger than grains in the diffuse ISM with an upper cutoff of $a_{\text{max}} \sim 0.25 - 0.3 \, \mu m$ due to grain growth as a result of accretion of gas species onto the grain surface and grain growth as a result of accretion of gas species onto the surface. Theoretical calculations predict grain growth to micron size in dense clouds (Hirashita & Li 2013). Numerous observations of dense prestellar cores show evidence of micron-sized grains through coreshine, i.e., a core becomes visible through scattered light in mid-infrared (e.g., Pagani et al. 2010; Lefèvre et al. 2020) and dust opacity increasing with column density in Herschel measurements (e.g., Roy et al. 2013; Ysard et al. 2013).

Based on our analysis of grain alignment for starless dense cores, if dust polarization is still detected at large $A_V$, then grain growth must occur such that $a > a_{\text{align}}$. Various observations of dust polarization reveal the existence of grain alignment in starless cores at larger extinctions of $A_V \sim 20$ (Wang et al. 2017; Kandori et al. 2018; Pattle et al. 2019), which is evidence of grain growth as implied from Equation (54).

Equation (54) shows that the maximum extinction at which grains can remain aligned increases with $a_{\text{max}}$. Therefore, if grain growth occurs in dense MCs, one expects such alignment even at large $A_V$. The existence of aligned large grains in dense MCs produces the polarization at large $A_V$, changing the slope of the polarization fraction at larger $A_{V,\text{max}}$.

Figure 12 illustrates the expected variation of the polarization fraction (arbitrary unit) with the visual extinction expected from grain alignment and disruption by RATs, described by $p \propto A_V^{\xi}$, for a starless core with two values of the maximum grain size (blue lines) and a protostellar core (orange lines). Shaded region represents the range of $A_V$ where grain alignment by RATs is completely lost for the protostar case. Slope changes to $\xi = 1$ when grain alignment is completely lost (dotted vertical line). Internal radiation induces alignment of grains near the source, changing the slope from $\xi = 1$ to $\xi = 0$ in the absence of RATD and to $\xi > 0$ in the presence of RATD. Uniform magnetic field geometry is assumed.

6 Indeed, simulations of polarized emission by dust grains aligned by RATs in Bok globules in Brauer et al. (2016) confirm that grain growth is required in order to explain the observed polarization.
(RATD), the slope steepens to $\xi > 0$ (dashed orange line). In a realistic situation, there may exist an intermediate period between the steep slope of $\xi = 1$ and $\xi = 0$ where the effect of the internal source compensates for the loss of alignment due to the aSRF.

Finally, note that the average dust temperature $T_d$ is usually inferred from fitting the SED of thermal dust emission. Therefore, one can make use of this observational parameter to constrain the maximum grain size. Indeed, the radiation strength is approximately given by $U = (T_d/T_d,0)^6$, and Equation (26) yields

$$a_{\text{max}} > a_{\text{align}} \simeq 0.055 \bar{\rho}^{-1/7} \left( \frac{\gamma - 1}{n_1 T_1} \right)^{2/7} \left( \frac{\bar{\lambda}}{1.2 \, \mu m} \right)^{1/7} \times \left( \frac{T_d}{16.4 \, K} \right)^{-12/7} \mu m, \quad (58)$$

where the infrared damping is disregarded due to its subdominance in starless dense clouds (see Equation (22)). For example, if observations toward a starless core suggest $T_d \sim 15 \, K$, Equation (58) implies $a_{\text{max}} > a_{\text{align}} = 0.45 \, \mu m$ and $0.85 \, \mu m$ for $n_1 = 10^6$, $10^7 \, \text{cm}^{-3}$, respectively, assuming $\gamma = 0.3$ and $\bar{\lambda} \sim 2 \, \mu m$ for the attenuated ISRF. Therefore, we conclude that grain growth must occur in these dense regions if the polarization slope is $\xi < 1$.

7. Summary

We study alignment and rotational disruption of dust grains by radiative torques and the implications for understanding the origins of polarization holes in dense MCs. The main findings of our results are summarized as follows:

1. Using RAT alignment theory, we derive analytical formulae for the minimum size of aligned grains by RATs as a function of the local parameters, including gas density, temperature, visual extinction $A_V$, and the radiation spectrum at the surface of a cloud. Our simple analytical formulae can be used to estimate minimum grain size for alignment and disruption by RATs for arbitrary local physical parameters.

2. We apply our analytical formulae for a dense molecular cloud without embedded sources, and find excellent agreement with numerical results. The grain alignment size increases with increasing local density and visual extinction from the surface.

3. We derive an analytical formula for the maximum visual extinction where grain alignment still exists in starless MCs, which depends on the maximum grain size, gas density, and the ambient radiation field.

4. The loss of grain alignment in starless cores is expected to result in a decrease of polarization with increasing optical depth, which reproduces the polarization hole in starless cores. Therefore, the detection of polarization from dense regions of high extinction implies grain growth to larger than the alignment size.

5. For dense clouds with an embedded source, we demonstrate that the minimum of aligned grains first decreases slowly in the envelope and then accelerates when entering a central region with constant density. Therefore, the polarization degree of dust emission increases with increasing emission intensity.

6. We find that rotational disruption of large grains into smaller ones by RATs (i.e., RATD effect) can occur toward the central source. The effect is more efficient for hot cores around protostars.

7. We find that the popular polarization hole observed toward protostars is inconsistent with the classical RAT theory. However, the decrease of polarization induced by the RATD effect can reproduce such a polarization hole without requiring an appeal to magnetic field tangling.

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