Gamma-Ray Burst Afterglows: Time-varying Extinction, Polarization, and Colors due to Rotational Disruption of Dust Grains

Thiem Hoang1,2,*, Nguyen Chau Giang3, and Le Ngoc Tram3,4,∗
1 Korea Astronomy and Space Science Institute, Yuseong-gu, Daejeon 34055, Republic of Korea; thiemhoang@kasi.re.kr
2 Korea University of Science and Technology, 217 Gajeong-ro, Yuseong-gu, Daejeon, 34113; Republic of Korea
3 University of Science and Technology of Hanoi, VAST, 18 Hoang Quoc Viet, Vietnam
4 SOFIA-USRA, NASA Ames Research Center, MS 232-11, Moffett Field, 94035 CA, USA

Received 2019 December 30; revised 2020 March 26; accepted 2020 April 17; published 2020 May 20

Abstract

Prompt optical emission of gamma-ray bursts (GRBs) is known to have important effects on the surrounding environment. In this paper, we study rotational disruption and alignment of dust grains by radiative torques (RATs) induced by GRB afterglows and predict their signatures on the observational properties. We first show that large grains (size >0.1 μm) within a distance d < 40 pc from the source can be disrupted into smaller grains by the RAdiative Torque Disruption (RATD) mechanism. We then model the extinction curve of GRB afterglows and find that optical-near-infrared extinction decreases, and ultraviolet (UV) extinction increases due to the enhancement of small grains. The total-to-selective visual extinction ratio, R_V, is found to decrease from the standard value of ~3.1 to ~1.5 after disruption time t_{disr} < 10^4 s. Next, we study grain alignment by RATs induced by GRB afterglows and model the wavelength-dependence polarization produced by grains aligned with magnetic fields. We find that optical-NIR polarization degree first increases due to enhanced alignment of small grains and then decreases when RATD begins. The maximum polarization wavelength, \lambda_{max}, decreases rapidly from the standard value of ~0.55 μm to ~0.15 μm over alignment time of t_{align} < 30 s due to enhanced alignment of small grains. Our theoretical predictions can explain various observational properties of GRB afterglows, including steep extinction curves, time-variability of colors, and optical rebrightening of GRB afterglows.

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629); Interstellar dust extinction (837); Interstellar dust (836); Starlight polarization (1571); Light curves (918); Supernovae (1668)

1. Introduction

Gamma-ray bursts (GRBs) are among the most luminous transient events in the universe. GRBs are thought to originate from a highly relativistic jet powered by a central engine (black hole or a highly magnetized neutron star–magnetar). During the burst (of ~10–100 s duration for long GRBs), prompt emission from X-ray to ultraviolet (UV)-optical wavelengths is also observed. After the prompt phase, GRB afterglows are emitted due to the interaction of relativistic jets with the ambient medium, including radiative cooling of reverse shocks and then forward shocks (Meszaros & Rees 1997). GRB afterglows can last up to days and, thus, offer an essential window to study the local environments around GRBs, which are required to understand the progenitors and emission mechanism of GRBs.

The effects of dust extinction are particularly important for understanding the nature and progenitor of GRBs because GRBs are expected to occur in star-forming dusty regions (Paczynski 1998). Indeed, only about 60% of Swift GRBs are detected in optical wavelengths, whereas X-ray detection of GRBs is more than 95% (Gehrels et al. 2009). This leaves about 40% of optical GRBs undetectable, so-called “dark” GRBs. The leading reason for this lies in the attenuation of optical photons by intervening dust (see Draine & Hao 2002 and reference therein).

GRB afterglows also offer a unique probe to study gas and dust properties in the interstellar medium (ISM) of high-redshift galaxies (i.e., z > 2) due to their stable, highest intrinsic luminosity (see Schady 2017 and reference therein). Observations show that the wavelength-dependent extinction (extinction curve) toward individual GRBs is described by a Small Magellanic Cloud (SMC)-like curve with a steep far-UV rise, which suggests the predominance of small grains in the local environment (e.g., Schady et al. 2012; Heintz et al. 2017; Zafar et al. 2018). The question of how small grains are predominant in the local environment of GRBs is still unknown. Similar to type Ia supernovae (SNe Ia), we expect that intense radiation from GRBs would have an important effect on the surrounding dust (Hoang et al. 2019).

The effect of prompt optical-UV emission from GRBs on surrounding dust was first studied by Waxman & Draine (2000), where the authors found that dust grains within 10 pc can be sublimated within 10 s from the burst. Later, Fruchter et al. (2001) studied dust destruction by grain heating and charging (i.e., Coulomb explosions) due to X-rays, where the latter mechanism is found to be more efficient. However, the effect of grain-size dependence of photoelectric yield by X-rays (Weingartner et al. 2006; Hoang et al. 2015b) is not considered in Fruchter et al. (2001). Detailed modeling of the time-dependent dust extinction due to the thermal sublimation and ion-field emission by the optical-UV flash (i.e., prompt emission) was presented in Perna et al. (2003), where the authors found that dust extinction decreases significantly by t ~ 10 s from the start of the burst.

Early-time observations of GRB afterglows (e.g., GRB 111209A by Stratta et al. 2013, GRB 120119A by Morgan et al. 2014) show a significant red-to-blue color change within ~200–500 s after the prompt emission phase. Moreover, Morgan et al. 2014 found a significant decrease of visual extinction A_V over a time period of t ~ 10–100 s, which is...
proposed as the first evidence of dust destruction toward GRB 120119A. In particular, late-time observations usually reveal a rebrightening in the optical-NIR light curves of GRB afterglows (Greiner et al. 2013; Nardini et al. 2014; Melandri et al. 2017; Kann et al. 2018). The origin of such an optical rebrightening remains elusive (see, e.g., Nardini et al. 2011). Previous studies suggest possible origins, including intrinsic processes related to the central engine of GRBs, external shocks due to the interaction of the relativistic jet with the ambient medium (see, e.g., Berger et al. 2003; Melandri et al. 2017) or from varying-dust reddening due to dust destruction (Draine & Salpeter 1979; Waxman & Draine 2000).

Very recently, Hoang et al. (2019) discovered a new mechanism of grain destruction, which is termed RAdiative Torque Disruption (RATD). The RATD mechanism, which is based on the centrifugal force within rapidly spinning grains spun-up by radiative torques (Draine & Weingartner 1996; Lazarian & Hoang 2007; Hoang & Lazarian 2009), can break a large grain into numerous smaller fragments and requires lower radiation intensity than sublimation to be effective. As a result, we expect that the long UV-optical afterglows (up to $10^5$ s) after the UV flash can disrupt grains at much later times and farther distances from the central source than previous mechanisms. The first goal of this paper is, thus, to quantify the effect of the disruption of dust grains in the surrounding environment by GRB afterglows and model the time-dependent dust extinction toward GRB afterglows.

Polarimetry is a powerful tool to study the emission mechanism and the geometry of GRB engines. Constraining the geometry of GRB progenitors is particularly important for gravitational wave (GW) astrophysics because GWs are expected to arise from the asymmetric collapse of the iron core of massive stars. Yet, a critical challenge is that the intrinsic polarization of GRB afterglows is uncertain, depending on the geometry and magnetic fields, whereas foreground polarization by circumstellar and interstellar dust in the host galaxy may be dominant. Moreover, numerous observations show time variation of the optical polarization of GRB afterglows (e.g., Barth et al. 2003), which is explained by means of varying magnetic fields in the jet (see Laskar et al. 2019 for a review). However, as found in Giang et al. (2020) for SNe Ia, we expect that dust polarization due to alignment of dust grains by GRB afterglows would vary with time, which challenges the standard explanation based on the variation of the magnetic fields. Therefore, our second goal is to exploit the popular theory of grain alignment and perform detailed modeling of dust polarization arising from grains aligned by GRB afterglows.

The structure of this paper is as follows. We will briefly describe the time-varying luminosity of GRB afterglows and the disruption mechanism in Section 2. In Sections 3 and 4, we present our modeling of time-variation extinction and polarization of GRB afterglows due to grain alignment and disruption by radiative torques. In Section 5, we study the effect of grain disruption by the RATD mechanism on the observed light curve of GRB afterglows. An extended discussion, including a comparison of our theoretical results with observational properties of GRB afterglows, is presented in Section 6. A summary of our main results is given in Section 7.

2. Radiative Torque Disruption of Grains by GRB Afterglows

2.1. Time-dependent Luminosity of GRB Afterglows

The luminosity of GRB afterglows due to the reverse shock (RS) can be described by

$$\nu L_\nu \propto \frac{4 (t/t_0)^{\alpha_{RS}}}{(1 + (t/t_0)^{\alpha_{RS}})^{\beta}} \left( \frac{h\nu}{13.6 \text{ eV}} \right)^{1+\beta},$$

where $\alpha_{RS}$ is the RS slope, the spectra index $\beta \sim -0.5$ is usually adopted, and $L_0$ is the UV-optical luminosity flash at the observed peak brightness $t_0$ (Draine & Hao 2002). For GRB 190114C with $\alpha_{RS} = 1.5$, $L_0 \sim 5 \times 10^{49}$ erg s$^{-1}$ with a typical observed peak brightness of $t_0 = 10$ s (Laskar et al. 2019). For $t \gg t_0$, $\nu L_\nu \propto t^{-1.5}$. It can be seen that even at $t \sim 10^3 t_0 = 10^4$ s (or ~3 hr), the luminosity is still significant with $\nu L_\nu \sim 10^{11} L_\odot$.

The luminosity of emission from radiative cooling of the forward shock (FS) is described by a shallower function of time (Fraija et al. 2019; Laskar et al. 2019),

$$\nu L_\nu = L_{FS,trans} \left( \frac{t}{t_{trans}} \right)^{\alpha_{FS}} \left( \frac{h\nu}{13.6 \text{ eV}} \right)^{1+\beta},$$

where $\alpha_{FS}$ is the slope for the FS stage, $L_{FS,trans}$ is the bolometric luminosity at transition time ($t_{trans}$) from the RS to FS. We adopt $\alpha_{FS} = -0.8$ for GRB 190114C (Laskar et al. 2019) and get $L_{FS,trans} = 2.53 \times 10^{47}$ erg s$^{-1}$ at the transition time of $t_{trans} = 864$ s or 0.01 day for the case of $t_0 = 10$ s.

The bolometric luminosity of GRB afterglows then can be evaluated as

$$L_{bol} = \int_{1 \text{ eV}}^{13.6 \text{ eV}} L_\nu \, d\nu,$$

and the mean wavelength is given by

$$\bar{\lambda} = \frac{\int_{1 \text{ eV}}^{13.6 \text{ eV}} \lambda L_\lambda \, d\lambda}{\int_{1 \text{ eV}}^{13.6 \text{ eV}} L_\lambda \, d\lambda}.$$

Using $\lambda L_\lambda = \nu L_\nu \propto \nu^{1+\beta} \propto \nu^{1+\beta}/\lambda^{1+\beta}$ (see Equations (1) and (2)), one obtains

$$\bar{\lambda} = \int_{1 \text{ eV}}^{13.6 \text{ eV}} \lambda^{-(\beta+1)} \, d\lambda = \frac{\beta + 1}{\beta} \lambda_{up}^{\beta} \lambda_{low}^{\beta-1},$$

where $\lambda_{low} = 0.091 \mu$m and $\lambda_{up} = 1.24 \mu$m.

Therefore, the mean wavelength becomes

$$\bar{\lambda} = \frac{\beta + 1}{\beta} \frac{\lambda_{up} - \lambda_{low}}{\lambda_{up}^{\beta-1} - \lambda_{low}^{\beta-1}},$$

which yields $\bar{\lambda} = 0.336 \mu$m for $\beta = -0.5$.

2.2. The RATD Mechanism

A dust grain of irregular shape exposed to an anisotropic radiation field experiences radiative torques (Dolginov & Mitrofanov 1976) that can spin up grains to suprathermal rotation (Draine & Weingartner 1996) and align dust grains. An
analytical model of RAdiative Torques (RATs) is developed by Lazarian & Hoang (2007), and numerical calculations of RATs for many irregular shapes are presented by Herranen et al. (2019). An experimental test of spin-up by RATs was conducted in Abbas et al. (2004). Hoang et al. (2019) discovered that, in an intense radiation field, the grain rotation rate driven by RATs can be sufficiently large such that induced centrifugal stress can exceed the maximum tensile strength of grain material and disrupt the grain into small fragments (i.e., RATD mechanism). A detailed description of the RATD mechanism is presented in Hoang et al. (2019), and its application for type Ia supernovae (SNe Ia) is shown in Giang et al. (2020). Here, we only briefly describe the RATD mechanism for the reference.

Let $a$ be the effective grain size defined as the radius of an equivalent spherical grain that has the same volume as an irregular grain. The angular velocity of irregular grains spun-up by RATs is obtained by solving the equation of motion (Hoang et al. 2019),

$$\frac{Id\omega}{dt} = \Gamma_{\text{RAT}} - \frac{I\omega}{\tau_{\text{damp}}},$$

where $I = 8\pi \rho a^2 / 15$ is the grain inertia moment (where $\rho$ is the mass density of grain material), the radiative torque $\Gamma_{\text{RAT}}$ is a function of time because of the time-varying luminosity of GRB afterglows, and $\tau_{\text{damp}}$ is the characteristic timescale of grain rotational damping induced by gas-grain collisions and IR emission (see Hoang et al. 2019 for details).

A dust grain spinning at angular velocity $\omega$ is disrupted when induced centrifugal stress $\sigma = \rho a^2 \omega^2 / 4$ exceeds the maximum tensile strength of grain material, $S_{\text{max}}$. The value of $S_{\text{max}}$ depends on the grain material and internal structure. It can vary from $S_{\text{max}} = 10^{19} \text{erg cm}^{-3}$ for ideal materials, i.e., diamond (Burke & Silk 1974; Draine & Salpeter 1979) to $S_{\text{max}} \sim 10^9 - 10^{10} \text{erg cm}^{-3}$ for polycrystalline bulk solid (Hoang et al. 2019) and $S_{\text{max}} \sim 10^6 - 10^8 \text{erg cm}^{-3}$ for composite grains (Hoang 2019). In this paper, we take $S_{\text{max}} = 10^9 \text{erg cm}^{-3}$ as a typical value for large grains. Then, the critical angular velocity at which rotational disruption occurs is obtained by setting $\sigma$ equal to $S_{\text{max}}$, which yields

$$\omega_{\text{disr}} = \frac{2}{a} \left( \frac{S_{\text{max}}}{\rho} \right)^{1/2} \approx 3.65 \times 10^{-9} a^{-1/2} \rho^{1/2} S_{\text{max},7}^{1/2} \text{ rad s}^{-1},$$

where $a_5 = a/(10^{-5} \text{cm})$, $\rho = \rho/(3 \text{ g cm}^{-3})$, and $S_{\text{max},7} = S_{\text{max}}/(10^7 \text{ erg cm}^{-3})$.

One can see that for the same density and maximum tensile strength, small grains need to be spun-up to a higher critical speed than large grains in order to be disrupted. For example, for $S_{\text{max}} = 10^9 \text{erg cm}^{-3}$, grains of $a \approx 0.25 \mu m$ are disrupted when $\omega \gtrsim 1.46 \times 10^5 \text{rad s}^{-1}$, but small grains of $a \sim 0.01 \mu m$ must be spun-up to $\omega \gtrsim 3.65 \times 10^9 \text{rad s}^{-1}$. Moreover, stronger grains with higher $S_{\text{max}}$ are more difficult to disrupt than weak grains with lower $S_{\text{max}}$. For instance, the value of $\omega_{\text{disr}}$ must be increased to $1.46 \times 10^9 \text{rad s}^{-1}$ and $3.65 \times 10^9 \text{rad s}^{-1}$ for grains of $0.25 \mu m$ and $0.01 \mu m$, respectively, assuming $S_{\text{max}} = 10^9 \text{erg cm}^{-3}$.

Let $U = u_{\text{rad}}/u_{\text{SR}}$ be the strength of a radiation field where $u_{\text{SR}} = 8.64 \times 10^{-13} \text{erg cm}^{-3}$ is the energy density of the average interstellar radiation field (ISRF) in the solar neighborhood (Mathis et al. 1983). For strong radiation fields of $U \gg 1$, damping of grain rotation is dominated by IR emission, and the gas damping can be disregarded (see Hoang et al. 2019 for details). Thus, the critical size of rotational disruption by RATD, $a_{\text{disr}}$, can be given by an analytical formula (Hoang 2019; Hoang et al. 2019),

$$\left( \frac{a_{\text{disr}}}{0.1 \mu m} \right)^{2.7} \approx 2 \times 10^{-4} \gamma^{-1} L_{10}^{-1/3} S_{\text{max},7}^{1/2} \mu_{0.5}^{-1.7} U_{10}^{1/3},$$

where $\gamma$ is the anisotropy degree of the radiation field ($0 \leq \gamma \leq 1$), $L_{0.5} = \lambda / (0.5 \mu m)$, $U_{10} = U/(10^6)$. The above equation is valid for $a_{\text{disr}} \lesssim \lambda / 1.8$. We also disregard the potential existence of very large grains (size $a \gtrsim 1 \mu m$) in the surrounding environment, so RATD can disrupt all grains above $a_{\text{disr}}$.

One can see that the grain disruption size increases with distance because of the decrease of the radiation energy density as $u_{\text{rad}} \propto 1/d^2$. For an UV-optical flash of luminosity $L_{\text{bol}} \sim 10^{50} \text{erg s}^{-1}$, the radiation strength is $U \sim 10^9 d_{pc}^{-2}$, where $d_{pc}$ is the distance given in units of parsecs. For weak grains of $S_{\text{max}} = 10^7 \text{ erg cm}^{-3}$, Equation (7) yields $a_{\text{disr}} = 0.0025 \mu m$ for $d = 10$ pc and $a_{\text{disr}} \approx 0.045 \mu m$ for $d = 100$ pc. For stronger grains of $S_{\text{max}} = 10^9 \text{ erg cm}^{-3}$, the disruption size increases to $a_{\text{disr}} = 0.006 \mu m$ and $0.01 \mu m$ at these distances. In realistic situations, the luminosity of GRB afterglows varies with time, as given by Equations (1) and (2). Thus, the disruption size will be obtained by numerically solving the equation of motion (Equation (5)) instead of using Equation (7).

The disruption time for grains of size $a_{\text{disr}}$ can be defined as the time required to spin up the grains to $\omega_{\text{disr}}$.

$$t_{\text{disr}} = \frac{I d\omega}{dt} = \frac{I\omega_{\text{disr}}}{\Gamma_{\text{RAT}}} \approx 318 \rho^{1/2} S_{\text{max},7}^{-1/2} \left( \frac{a_{\text{disr}}}{0.1 \mu m} \right)^{-0.7} \times S_{\text{max},7}^{1/2} \left( \gamma U_{10}^{-1} \right)^{-1} \text{ s}.$$

Equation (8) reveals that large grains of $a = 0.25 \mu m$ at distance $d$ can be disrupted in $t_{\text{disr}} = 0.085 d_{pc}^{-2} S_{\text{max},7}^{1/2} \text{ s}$. For weak grains of $S_{\text{max}} = 10^7 \text{ erg cm}^{-3}$, the disruption time is $t_{\text{disr}} \sim 8.5 \text{ s}$ at $d = 10$ pc and $\sim 4 \text{ min}$ at $50$ pc. For strong grains of $S_{\text{max}} = 10^9 \text{ erg cm}^{-3}$, the disruption time increases to $t_{\text{disr}} \sim 1.5 \text{ min}$ and $\sim 36 \text{ min}$ at $d = 10$ and $50$ pc, respectively.

3. Extinction of GRB Afterglows

In this section, we study the effect of RATD on the extinction of GRB afterglows for an optically thin environment and disregard the light attenuation by intervening dust. Thus, all dust grains are exposed to the intrinsic radiation of GRB afterglows.

3.1. Grain Disruption Size

To calculate the grain disruption size $a_{\text{disr}}$ for a variable size like GRB afterglows, we solve Equation (5) to obtain the temporal angular velocity $\omega(t)$ for a range of grain sizes using the luminosity $L_{\text{bol}}$ given by Equations (1) and (2). We then compare $\omega(t)$ with the critical angular velocity of disruption given by Equation (6) to obtain $a_{\text{disr}}$. The disruption time $t_{\text{disr}}$ is also determined.

Figure 1 (upper panel) shows the grain disruption size due to the RATD effect as a function of cloud distance at different
Figure 1. Upper panel: grain disruption size by RATD as a function of dust cloud distance at different times since the GRB. Lower panel: variation of grain disruption size with time for different cloud distances from 11 pc to 35 pc. The vertical dotted lines indicate the disruption distance (upper panel) and the disruption time (lower panel). Here, maximum tensile strength $S_{\text{max}} = 10^7 \text{ erg cm}^{-3}$ and the peak luminosity of GRB afterglows at $t_0 = 10$ s are assumed.

Disruption begins at $t_{\text{dist}} \sim 10$ s, at which $a_{\text{disr}}$ starts to decrease from the original value to very small grains of size $a_{\text{disr}} \sim 0.005 \mu m$ after 5 hr. At larger distances of $d = 15$ and 25 pc, grain disruption starts later, and the disruption size achieves $a_{\text{disr}} \sim 0.015 \mu m$ and $0.06 \mu m$ at $t \sim 5$ hr, respectively. At distance $d = 35$ pc, grain disruption only occurs after $t \sim 5.2$ hr, and the disruption occurs for large grains of $a > a_{\text{disr}} \sim 0.1 \mu m$ only.

Figure 2 (upper panel) shows the grain disruption size after one day for different cloud distances, assuming $t_0 = 10$ s and different values of $S_{\text{max}}$. The active region of RATD reduces from 40 pc for weak grains of $S_{\text{max}} = 10^7 \text{ erg cm}^{-3}$ to 25 pc for $S_{\text{max}} = 10^8 \text{ erg cm}^{-3}$ and $\sim10–13$ pc for $S_{\text{max}} \geq 10^9 \text{ erg cm}^{-3}$. This arises from the fact that rotational disruption depends closely on the tensile strength of grain materials as shown by Equation (6).

Figure 2 (lower panel) shows the grain disruption size versus time for clouds at 15 pc, assuming $S_{\text{max}} = 10^7 - 10^9 \text{ erg cm}^{-3}$. Grains with higher $S_{\text{max}}$ begin to be disrupted by RATD later compared to weak grains of lower $S_{\text{max}}$. For instance, grains with $S_{\text{max}} = 10^7 \text{ erg cm}^{-3}$ begin the disruption after $t_{\text{disr}} = 15.39$ s and have a grain disruption size of...
\[ a_{\text{disr}} = 0.01 \mu m \] after one day. However, the disruption time increases to \( t_{\text{disr}} = 1.67 \) min, and \( a_{\text{disr}} = 0.05 \mu m \) for grains with \( S_{\text{max}} = 10^8 \) erg cm\(^{-3}\). Figure 3 shows the variation of grain disruption size over time for the different values of \( t_0 \), assuming \( S_{\text{max}} = 10^8 \) erg cm\(^{-3}\) and cloud distance \( d = 15 \) pc. The grain disruption occurs earlier if the luminosity peaks earlier (smaller \( t_0 \)), which arises from the decreases of the luminosity with peak time as \( L_{bol}(t) / t_0 \) (see Equation (1)). For example, with \( t_0 = 10 \) s, grains of \( a = 0.25 \mu m \) will be disrupted after \( t_{\text{disr}} = 15 \) s, and one obtains \( a_{\text{disr}} = 0.02 \mu m \) at 1000 s. However, for \( t_0 = 30 \) s, the 0.25 \( \mu m \) grains are disrupted at \( t_{\text{disr}} \sim 60 \) s, and \( a_{\text{disr}} = 0.04 \mu m \) disrupted at \( \sim 1000 \) s.

### 3.2. Extinction Curves

To model the extinction of GRB afterglows by intervening dust between the source and the observer, we adopt a popular mixed-dust model consisting of astronomical silicate and carbonaceous grains (see Weingartner & Draine 2001; Draine & Li 2007).

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

\[
A(\lambda) = \sum_{j=\text{spheroidal}} \int_{a_{\min}}^{a_{\max}} C_{\text{ext}}(a) \left( \frac{1}{n_H} \right) da, \tag{9}
\]

where \( a \) is the effective grain size, \( dn^i / da \) is the grain-size distribution of dust component \( j \), \( C_{\text{ext}} \) is the extinction cross section taken from Hoang et al. (2013), assuming oblate spheroidal grains with axial ratio \( r = 2 \), and \( n_H \) is the total column density of hydrogen along the line of sight. Here, the maximum grain size \( a_{\max} = \min(a_{\text{disr}}, a_{\max,\text{MRN}}) \) is the upper cutoff of the grain-size distribution in the presence of RATD, and \( a_{\max,\text{MRN}} = 0.25 \mu m \) is the upper cutoff of the MRN distribution (Mathis et al. 1977).

Due to the RATD effect, dust extinction given by Equation (9) is time-dependent because \( a_{\text{disr}} \) and then \( dn^i / da \) change with time. In order to glean insights into the effect of RATD on the time-varying extinction of GRB afterglows, we consider a single slab model, such that the small variation of \( a_{\text{disr}} \) within the dust cloud can be ignored. Nevertheless, in realistic situations, there may exist several intervening dust clouds, and this issue will be discussed in Section 6.

To model the grain-size distribution modified by RATD, we adopt a power law \( dn^i / da = C_j n_H a^\eta \) where \( C_j \) is the normalization constant of dust component \( j \), and \( \eta \) is the power-law slope (Mathis et al. 1977). For the standard grain-size distribution (Mathis et al. 1977), one has \( C_{\text{sil}} = 10^{-25.1} \) cm\(^{-2.5}\) for silicate grains and \( C_{\text{carb}} = 10^{-25.13} \) cm\(^{-2.5}\) for carbonaceous grains and \( \eta = -3.5 \). To account for the RATD effect, we fix the constant \( C \) and change the slope \( \eta \). Such a new slope \( \eta \) is determined by the dust mass conservation as given by (see Giang et al. 2020 for more details)

\[
\int_{a_{\min}}^{a_{\text{disr}}} a^\eta da = \int_{a_{\min}}^{a_{\max,\text{MRN}}} a^\eta da^{3.5}da, \tag{10}
\]

which yields

\[
a_{\text{disr}}^{\frac{4}{\eta+1}} - a_{\min}^{\frac{4}{\eta+1}} = a_{\max,\text{MRN}}^{\frac{0.5}{\eta+0.5}} - a_{\min}^{\frac{0.5}{\eta+0.5}}. \tag{11}
\]

Figure 4 illustrates the time variation of the extinction curve when the grain-size distribution is modified by RATD. The optical to near-infrared (NIR) extinction is seen to decrease gradually with time due to the removal of large grains by RATD. In contrast, UV extinction increases due to the enhancement in the abundance of small grains with respect to larger ones.

Figure 5 shows the variation of \( A(\lambda, t) / A(\lambda, 0) \) with time from far-ultraviolet (FUV) through optical to (NIR) bands for grains located at distances between 11 pc and 35 pc from the source,\(^5\) assuming \( S_{\text{max}} = 10^8 \) erg cm\(^{-3}\) and \( t_0 = 10 \) s. We choose the central wavelength of the UV range, such as \( \lambda = 0.15 \) \( \mu m \) for the FUV band, \( \lambda = 0.25 \) \( \mu m \) for the mid-UV (MUV) band, and \( \lambda = 0.3 \) \( \mu m \) for the near-UV (NUV) band, to study the effect of RATD on UV extinction.

---

\(^5\) Here, we start with clouds from 11 pc because thermal sublimation induced by prompt GRB emission can clear out all grains within 10 pc (Waxman & Draine 2000).
Figure 5 shows that dust extinction remains constant for \( t \leq t_{\text{disr}} \) (before RATD) and changes significantly with time after RATD occurs. One can see that optical-NIR extinction decreases immediately to smaller values because of the quick removal of large grains of size \( a \gtrsim 0.1 \mu m \) by RATD. In contrast, the extinction value in other bands (i.e., the U, B, and UV bands), first increases due to the enhancement of small grains then decreases later when these small grains are again fragmented into smaller ones. Dust extinction in all bands reaches a saturated value after a long time when RATD ceases. For example, at \( d = 15 \) pc, \( A(\lambda) \) stops to change from \( \sim 200 \) \( s \) to one day, which corresponds to the period that \( a_{\text{disr}} \) only decreases from \( 0.02 \mu m \) to \( 0.01 \mu m \) (see Figure 1, lower panel). For more distant clouds, the variation of dust extinction begins at later times due to larger \( t_{\text{disr}} \). For instance, the extinction begins to change after \( t_{\text{disr}} = 13 \) \( s \), \( 40 \) \( s \), and \( 9 \) minutes for \( d = 15 \), \( 25 \), and \( 35 \) pc, respectively.

### 3.3. Time Variability of \( E(B - V) \) and \( R_V \)

Using \( A(\lambda, t) \) obtained in the previous section, we can calculate the color excess \( E(B - V, t) = A_B - A_V \) and the total-to-selective visual extinction ratio \( R_V = A_V / E(B - V, t) \). Here, \( A_V \) and \( A_B \) are dust extinction in the \( V \) and \( B \) bands at time \( t \).

Figure 6 shows the variation of \( E(B - V, t) / E(B - B, t = 0) \) with time for different cloud distances from \( 11 \) pc to \( 35 \) pc, assuming \( S_{\text{max}} = 10^7 \) erg cm\(^{-3} \) (upper panel) and \( S_{\text{max}} = 10^8 \) erg cm\(^{-3} \) (lower panel) and \( t_0 = 10 \) s. For a given cloud distance, the color excess remains constant until grain disruption begins at \( t \sim t_{\text{disr}} \). Subsequently, the ratio increases rapidly and then decreases to a saturated level when RATD ceases. For example, at distance \( d = 11 \) pc, the color excess starts to rise at \( t \sim 8.6 \) \( s \) and declines again to the saturated value at \( t \sim 10 \) min. The rising stage of \( E(B - V) \) is caused by the increase of \( A_B \) when grain disruption just starts that converts the largest grains into smaller ones. Soon after that, these small grains are further disrupted into smaller fragments, and both \( A_B \) and \( A_V \) decrease (see Figure 4), resulting in the decrease of \( E(B - V, t) \) with time. Higher tensile strength delays the grain disruption and, then, the variation of the color excess (see the lower panel). For instance, the time variation of \( E(B - V) \) for \( d \sim 15 - 25 \) pc increases from \( 13 \) to \( 561 \) \( s \) for grains with \( S_{\text{max}} = 10^7 \) erg cm\(^{-3} \) to \( 56 - 840 \) \( s \) for grains with \( S_{\text{max}} = 10^8 \) erg cm\(^{-3} \).

We note that the amplitude of the \( E(B - V, t) \) variation is within \( \sim 40\% \), which is different from the large change of \( A_V \) up to \( 80\% \) (Figure 5). This arises from the fact that grain disruption by RATD gradually modifies the grain-size distribution.

Figure 7 (upper panel) shows the variation of \( R_V \) with time for different cloud distances from \( 11 \) pc to \( 35 \) pc, assuming \( S_{\text{max}} = 10^7 \) erg cm\(^{-3} \) and \( t_0 = 10 \) s. For a given distance, one can see that \( R_V \) begins to decrease rapidly from its original value of \( 3.1 \) given by standard dust in ISM at \( t = t_{\text{disr}} < 10 \) min to smaller values of \( R_V \sim 0.5 - 1.5 \) due to RATD. The final value of \( R_V \) is larger for grains located farther away from the source.

Figure 7 (lower panel) shows the time variation of \( R_V \) during one day for clouds at \( 15 \) pc and different tensile strengths. The value of \( R_V \) decreases quickly with time for weak grains of \( S_{\text{max}} = 10^7 \) erg cm\(^{-3} \) and \( S_{\text{max}} = 10^8 \) erg cm\(^{-3} \), but \( R_V \) does not change for strong grains of \( S_{\text{max}} \gtrsim 10^9 \) erg cm\(^{-3} \).
4. Polarization of GRB Afterglows

4.1. Grain Alignment Size

Following the paradigm of RADiative Torque (RAT) alignment (see Andersson et al. 2015 and Lazarian et al. 2015 for recent reviews), dust grains subject to GRB afterglows can be aligned with the ambient magnetic field when they are spun-up to suprathermal rotation. Note that grains may be aligned with the long axis perpendicular to the radiation field (Lazarian & Hoang 2007). However, here, we stick to the traditional mechanism of grain alignment with the magnetic field and will discuss that effect in Section 6.8.

The suprathermal rotation condition is approximately given by (Hoang & Lazarian 2008, 2016)

$$\omega_{\text{RAT}} \geq 3 \omega_T,$$

where $$\omega_T$$ is the thermal angular velocity of dust grains at gas temperature $$T_{\text{gas}}$$ such that

$$\omega_T = \sqrt{\frac{2kT_{\text{gas}}}{I}},$$

$$\simeq 2.3 \times 10^5 \rho^{-1/2} a_s^{-5/2} \left( \frac{T_{\text{gas}}}{100 \text{ K}} \right)^{1/2} \text{ rad s}^{-1},$$

where $$k$$ is the Boltzmann constant.

For a given cloud with gas temperature $$T_{\text{gas}}$$, small grains have a higher suprathermal threshold than large grains. As a result, they require a higher radiation energy (i.e., closer clouds) to be efficiently aligned by RATs.

Based on Equation (12), the grain size at $$\omega_{\text{RAT}} = 3 \omega_T$$ is defined as the critical size of grain alignment, $$a_{\text{align}}$$. All grains larger than $$a_{\text{align}}$$ are assumed to be perfectly aligned (Hoang & Lazarian 2016). Following Hoang (2017), the grain alignment...
size is given by
\[
\left( \frac{a_{\text{align}}}{0.1 \, \mu m} \right)^{4.2} \approx 1.4 \times 10^{-5} \rho^{-1/2} \gamma^{-1/2} \chi_{0.5}^{1.7} U_{10}^{-1/3} \left( \frac{T_{\text{gas}}}{100 \, K} \right)^{1/2},
\]
(14)

where the dominance of IR damping over gas damping is used, which is valid for the intense radiation field of GRB afterglows. Above, we disregard the dependence of the rotation rate spun-up by RATs on the angle between the radiation direction and the magnetic field (Hoang & Lazarian 2009). Accounting for that effect would reduce the value of $\omega_{\text{RAT}}$ and slightly increase $a_{\text{align}}$. However, the time-variability of $a_{\text{align}}$ would not change significantly because it is determined by the varying luminosity of GRBs.

With the same assumption of GRB afterglows in Section 2, one can find that the grain alignment size increases with increasing cloud distance and gas temperature. For instance, the grain alignment size will be $a_{\text{align}} = 0.0023 \, \mu m$, $0.003 \, \mu m$, and $0.0034 \, \mu m$ for clouds at 10 pc, 50 pc, and 100 pc, respectively, assuming $T_{\text{gas}} = 100 \, K$. It will increase to $a_{\text{align}} = 0.0029 \, \mu m$, $0.0037 \, \mu m$, and $0.0042 \, \mu m$, respectively, for $T_{\text{gas}} = 500 \, K$.

Initially ($t = 0 \, s$), grains are aligned by the average interstellar radiation field ($\gamma = 0.1$ and $U = 1$) with $a_{\text{align}} \approx 0.051 \, \mu m$ (see, e.g., Equation (14)). The alignment time $t_{\text{align}}$ is defined as the time required for grains to be spun-up to suprathermal rotation intense radiation field of GRB afterglows (Hoang 2017; Giang et al. 2020).

\[
t_{\text{align}} = \frac{3\omega_T}{dJ/dt} \approx 0.6\rho^{1/2} \left( \frac{T_{\text{gas}}}{100 \, K} \right)^{1/2} \left( \frac{a_{\text{align}}}{0.1 \, \mu m} \right)^{-2.2} \frac{1}{\gamma U_{10}^{1/2}} \, s.
\]
(15)

We obtain an alignment time of $t_{\text{align}} \approx 0.0012 \, d_{10}^2 (T_{\text{gas}}/100 \, K)^{1/2} \, s$, which is very short for grains at $d \sim 1 \, pc$ from the source. For different clouds at 10 pc, 50 pc, and 100 pc, we get $t_{\text{align}} = 0.1213 \, s$, 3.4 s, and 13 s, respectively, assuming $T_{\text{gas}} = 100 \, K$. For a higher gas temperature of $T_{\text{gas}} = 500 \, K$, $t_{\text{align}}$ increases to 0.3 s, 7.5 s, and 30 s. However, we note that these estimates assume the constant luminosity of GRB afterglows, which overestimate the value of $a_{\text{align}}$ and $t_{\text{align}}$ compared to the realistic case of the time-varying luminosity of GRBs. From Equations (15) and (8), it follows that the alignment time is much smaller than the disruption time. This is obvious because the RAT alignment can occur at rotation rates (Equation (12)) much lower than RATD (see 6).

Figure 8 shows the variation of the grain alignment size $a_{\text{align}}$ during the first day for different cloud distances from 11 pc to 35 pc, assuming $T_{\text{gas}} = 100 \, K$. The alignment size first remains constant at $a_{\text{align}} \approx 0.055 \, \mu m$ given by the alignment of the average interstellar radiation until $t_{\text{align}}$. After that, it decreases rapidly to smaller values until $t \sim 100 \, s$ and then slows down later due to the decrease of the radiation intensity. For more distant clouds, $t_{\text{align}}$ becomes larger, and $a_{\text{align}}$ starts to decrease later due to a lower radiation intensity. For example, the alignment time increases from $\sim 1.33 \, s$ for grains at 11 pc to $\sim 3 \, s$ for grains at 35 pc. Also, after one day, RATs can align small grains of $a \sim 0.003 \, \mu m$ and $0.006 \, \mu m$ for the two above distances, respectively.

4.2. Polarization Curves

Observations (Chiar et al. 2006) and theoretical studies (Hoang & Lazarian 2016) reveal that carbonaceous grains are unlikely aligned with the ambient magnetic field due to their diamagnetic properties (see Lazarian et al. 2015 for a review). Therefore, we assume that carbonaceous grains are randomly oriented, and only silicate grains can be aligned by RATs. The degree of polarization is given by differential extinction by aligned grains along the line of sight is computed by
\[
\frac{P(\lambda)}{N_{\text{H}}} = 100 \int_{a_{\text{min}}}^{a_{\text{max}}} \frac{C_{\text{pol}}(a)f(a)\cos^2 \zeta}{\zeta} \frac{1}{n_{\text{H}}} \frac{da}{da_{\text{sil}}} \, da,
\]
(16)

where $C_{\text{pol}}$ is the polarization cross section, $f(a)$ is the effective degree of grain alignment for silicate grains of size $a$ (hereafter alignment function), and $\zeta$ is the angle between the magnetic field and the plane of the sky (see Hoang 2017). We take $C_{\text{pol}}$ computed for different grain sizes and wavelengths from Hoang et al. (2013).

We define the size-dependence degree of grain alignment by RATs as follows:
\[
f(a) = 1 - \exp \left[-\left( \frac{0.5a}{a_{\text{align}}} \right)^3 \right],
\]
(17)

where $a_{\text{align}}$ is given by Equation (14) (Hoang & Lazarian 2014; Hoang et al. 2015a). This alignment function returns $f(a) = 1$ (i.e., the perfect alignment) for large grains of size $a \gg a_{\text{align}}$ and approximates the size-dependence alignment degree computed from simulations for grains with enhanced magnetic susceptibility by Hoang & Lazarian (2016). Here, we take $a_{\text{max}} = \min(a_{\text{disr}}, a_{\text{max,MRN}})$ and $da_{\text{sil}}/da$ as used for dust extinction.

Above, we have assumed that small grains (i.e., $a < 0.05 \, \mu m$) can be perfectly aligned with the magnetic field.
if they can be spun-up to suprathermal rotation by RATs. However, such small grains may not have iron inclusions (Mathis 1986), and the degree of grain alignment induced by only RATs for ordinary paramagnetic grains may not be perfect if RAT alignment lacks high-J attractor points (Hoang & Lazarian 2016). Due to uncertainty in the magnetic properties of dust grains, our theoretical predictions in this section are considered upper limits of dust polarization.

Figure 9 illustrates the general variation of the polarization curve with time as a result of RAT alignment and RATD. As soon as the alignment by RATs starts to occur, the degree of polarization increases, and the peak wavelength shifts to shorter wavelengths due to an enhanced alignment of small grains. When RATD begins, the optical-NIR polarization is significantly reduced, but UV polarization increases due to the conversion of large grains into small grains. As a result, the polarization curve will narrow with time.

Figure 10 shows the time variation of the polarization degree of GRB afterglows, $P(\lambda, t)/P(\lambda, 0)$, evaluated in the different bands for three dust cloud distances, assuming $T_{\text{gas}} = 100$ K. After the alignment time, the polarization degree in all bands increases significantly due to the decrease of $a_{\text{align}}$ as a result of the enhanced radiation field, then it mostly saturates after about $t \lesssim 30$ s. After that, the disruption happens (see Figure 7, lower panel), which makes the optical/NIR polarization degree start to decline rapidly, but the UV polarization continues to rise due to the enhancement of small aligned grains and can decrease slightly later if its suitable grain size is removed, i.e., the case of UV polarization degree given by grains at 15 pc. All variations will stabilize when the grain disruption size reaches its saturated value after a long time. For a more distant cloud the polarization curve starts to change at a later time due to $t_{\text{align}}$ and $t_{\text{disr}}$. For example, the phase when grains are only aligned by RATs lasts from $t_{\text{align}} = 13$ s for clouds at 15 pc to nearly one minute and two hours for clouds at 25 pc and 35 pc, respectively. Besides, after one day, the polarization degree in the $R$ band only decreases 3–10 times for grains at 25 pc and 35 pc, but it is \~25 times for grains at 15 pc.
5. Effect of RATD on the Light Curves of GRB Afterglows

As shown in Section 3, RATD increases dust extinction in the FUV–NUV bands but decreases dust extinction in the optical-NIR bands due to the conversion of large grains into smaller ones. Such a variation of dust extinction by RATD would change the observed spectrum of GRB afterglows as well as their light curves. In this section, we apply the new extinction curves in the presence of RATD to study how they affect the observed light curve of GRB afterglows.

Let $\tau(\lambda, t) = A(\lambda, t)/1.086$ be the optical depth induced by dust extinction from an intervening cloud between the GRB and an observer, which is measured at time $t$ since the burst. The specific luminosity of GRB afterglows observed at time $t$ on Earth is given by

$$L_\lambda(t) = L_\lambda(0)e^{-\tau(\lambda,t)},$$ 

where $L_\lambda(0)$ is the intrinsic specific luminosity given by Equations (1) and (2).

For our calculations, we assume that the intervening cloud has a visual extinction of $A(V, t = 0) = 2$ mag, which corresponds to a total gas column density of $N_H = 3.14 \times 10^{21}$ cm$^{-2}$. The choice of $A(V, t = 0) = 2$ is intended to reflect a dusty environment surrounding GRBs. For a given $N_H$, one can calculate $\tau(\lambda)$ using $A(\lambda, t)$ calculated in Section (3.2), and the observed luminosity $L_\lambda(t)$ is calculated via Equation (18).

Figure 12 shows the time variation of the observed light curve from the FUV to $R$ bands after entering a dust cloud at 15 pc, 25 pc, and 35 pc, with (solid line) and without (dashed line) grain disruption.

One can see that after the disruption time of $t_{\text{disr}} = 13$ s for clouds at $d = 15$ pc, GRB afterglows suddenly brighten up to $\sim 3$ times in the visible-NIR bands compared with the no grain disruption case. The reason is that the reduction of the visible-NIR extinction will let more light escape from the dust, resulting in the increase of visible-NIR luminosity. In contrast, the increase of the UV extinction will block more short-wavelength photons, which makes GRB afterglows become “dimmer”, from three to five times, in the FUV–NUV band compared with the case of no dust disruption (Figure 12, upper panel).

When the cloud distance increases, these features will happen later and exhibit a smaller amplitude than those of nearby clouds (Figure 12, central and lower panel). Besides, at nearby clouds, i.e., $d \lesssim 15$ pc, the luminosity in the FUV and MUV bands can increase slightly after a long time compared to before ($\sim 100$ s), due to the disruption of small grains, while this does not happen with distant clouds, i.e., $d = 25$ pc and 35 pc. In addition, one may not obtain any change in the observed light curve if clouds are located very far from GRB afterglows, where RATD cannot destroy grains effectively, i.e., $d > 40$ pc.

6. Discussion

6.1. Comparison of RATD to Thermal Sublimation and Coulomb Explosion

GRBs are expected to explode in a dusty region (Morgan et al. 2014), such that intense radiation field of GRBs can have important effects on dust and gas in the surrounding environment. This, in turn, affects the observed light curves and color of GRB afterglows. Therefore, dust destruction by GRB afterglows was studied extensively in the literature.

Waxman & Draine (2000) first studied the sublimation of dust grains by prompt optical-UV emission of GRBs and found that dust grains located within a distance of $\sim 10$ pc could be completely evaporated. Later, Fruchter et al. (2001) studied dust destruction caused by X-ray irradiation and found that grains could be disrupted by X-ray heating and charging (i.e., Coulomb explosions) to distances of $\sim 10$ and $\sim 100$ pc, respectively. The active timescales of both sublimation and Coulomb explosions are short, $t \lesssim 10$–100 s, after the start of the burst. However, the issue of photoelectric yield by X-ray charging is not studied in detail in Fruchter et al. (2001). As shown in Hoang et al. (2015b), the yield for large grains of $a \sim 1$ $\mu$m is one order of magnitude lower than that of $a \sim 0.001$ $\mu$m. Thus, similar to grain sublimation, Coulomb explosions might be only efficient for small grains because those grains have a higher photoelectric yield and a lower critical charge for explosions (Hoang et al. 2015b).

In this paper, we study the rotational disruption of dust grains induced by the irradiation of optical-UV GRB afterglows using the radiative torque disruption (RATD) mechanism. We find that grains can be disrupted up to distances of $10^5$ cm$^{-3}$, i.e., the cloud is dense.
about 40 pc, on a timescale up to days, which is much longer than sublimation and Coulomb explosions caused by prompt GRB emission. The disruption time depends on grain size, the maximum tensile strength, and the grain distance to the source (see Figures 1 and 2).

One of the key differences between RATD and thermal sublimation and Coulomb explosions is that RATD reduces the abundance of large grains and increases the abundance of small and very small grains, while the total dust mass is constant. As a result, optical-NIR extinction decreases, but UV extinction increases with time (see Figure 4). On the other hand, sublimation transforms dust into gas and is more efficient for small grains, such that dust extinction at all wavelengths and color excess decreases with time (Perna & Lazzati 2002; Perna et al. 2003).

Both thermal sublimation and Coulomb explosions by X-rays can significantly change the dust properties during the prompt emission phase of GRBs of $t \lesssim 10-100$ s after the burst. As a result, very early phase observations are required to test the time variation of dust extinction and polarization by these mechanisms (Perna et al. 2003). In contrast, RATD relies on optical GRB afterglows that can last on longer timescales of days. Therefore, observational testing of RATD appears to be much easier.

6.2. Predictions of Observational Properties for GRB Afterglows Induced by RAT Alignment and RATD

Below, we summarize four main predictions for the observational properties of GRB afterglows induced by an intervening dust cloud when the effects of grain alignment and disruption by RATs due to intense GRB afterglows are taken into account.

6.2.1. Prediction 1: RATD Decreases Optical-NIR Extinction and $R_V$ over Time

In Section 3.2, we have shown that RATD can destroy large grains around GRB afterglows up to 40 pc for an optically thin environment. The depletion of large grains by RATD decreases the optical-NIR extinction but increases the UV extinction. Moreover, we predict that the values of $R_V$ gradually decrease from the standard value of $R_V = 3.1$ to $R_V \sim 1$ in the presence of RATD. Therefore, the extinction curves toward GRB afterglows that have a dust cloud nearby would be different from the standard Milky Way (MW) extinction curve, which should exhibit a steep far-UV rise due to a high abundance of small grains (see Figure 4).

6.2.2. Prediction 2: RATD Increases and Then Decreases the Color Excess of GRB Afterglows

Our theoretical results from Figure 6 predict that the color excess $E(B - V)$ changes with time. It first increases rapidly and then decreases with time after the peak. The peak of $E(B - V)$ depends on the cloud distance and grain properties.

6.2.3. Prediction 3: RATD Increases and Then Decreases Optical-NIR Polarization

Subject to an intense radiation of GRB afterglows, dust polarization first rises quickly due to the enhanced alignment of
small grains by RATs. At the same time, the peak wavelength $\lambda_{\text{max}}$ shifts to smaller wavelengths. This process continues from $t_{\text{align}}$ to $t_{\text{disr}}$. When RATD begins, the optical-NIR polarization decreases substantially due to the depletion of large grains, whereas UV polarization increases due to the increased abundance of small grains (see Figure 9). The exact values of $t_{\text{align}}$ and $t_{\text{disr}}$ depend on the radiation field, dust properties, and distance of dust clouds to the source.

6.2.4. Prediction 4: RATD Produces an Optical-NIR Rebrightening of GRB Afterglows

Due to the decrease of optical-NIR extinction, the observed flux of GRB afterglows in the optical-NIR bands is spontaneously increased after disruption time (see Figure 12). The RATD effect induces the rebrightening in the optical-NIR bands, which occurs at disruption time $t_{\text{disr}}$. The rebrightening time depends on the cloud distance to the source and dust properties (e.g., tensile strength) as shown in Figure 1.

6.3. Comparison of Observed Properties of GRB Afterglows with Model Predictions

First, observations of GRB 120119A by Morgan et al. (2014) show a decrease of visual extinction from $A_V \sim 1.55$ at $t \sim 10$ s to $A_V \sim 1.1$ at $t \sim 100$ s after the burst, corresponding to a decrease of 30% over a period of 10–100 s. Such a rate of the decrease is several times larger than theoretical predictions for the $t \sim 10–100$ s period using dust sublimation induced by prompt emission because sublimation is most efficient for $t < 10$ s (see Figure 5 in Perna et al. 2003). However, this fast decrease in $A_V$ is consistent with our first prediction (see, e.g., Figure 4). Moreover, photometric observations of GRB afterglows show that an SMC-like extinction curve with a steep far-UV rise is preferred for GRBs (Schady et al. 2012; Schady 2017 for a review; Heintz et al. 2017). Bolmer et al. (2018) also found that the extinction toward GRBs at redshifts $z > 4$ is best-fitted with an SMC-like extinction curve. In particular, previous studies (e.g., Zafar et al. 2018, 2019) show that the majority of the light of sight toward GRB afterglows has lower values of $R_V < 3.1$ (see Table 2 in Zafar et al. 2018). The observed features mentioned above require an increased abundance of small grains from the standard interstellar dust model (e.g., Schady et al. 2010). The conversion of large grains into smaller ones via RATD is a plausible mechanism to explain this feature (i.e., our first prediction).

Second, photometric observations of GRB afterglows usually show a significant red-to-blue color change after the trigger (see, e.g., Nardini et al. 2014), which is partly suggested to be a result of the photodestruction of surrounding grains (Morgan et al. 2014). However, the prevalent mechanisms of dust destruction cannot support this scenario due to the inconsistency between its timescale and the observed time. For example, Morgan et al. (2014) reported a significant red-to-blue color during 200 s after the burst toward GRB 120119A, and a similar effect is reported by Perley et al. (2010) for GRB 061126, which is longer than that predicted by previous dust destruction mechanisms. The observed feature is however consistent with our second prediction by RATD. As shown in Figure 6, our model of the time variation of color excess $E(B-V)$ for $S_{\text{max}} = 10^8$ erg cm$^{-3}$ and $d = 15 \sim 20$ pc can reproduce well their observational timescale.

Third, polarimetric observations usually report time variability of the optical polarization of GRB afterglows on a timescale of 100 s to days (see Covino & Gotz 2016 for details) compared with our theoretical model in the $R$ band, assuming a dust cloud at 15 pc and tensile strength $S_{\text{max}} = 10^8$ erg cm$^{-3}$. The original polarization degree in the $R$ band $P(t = 0)$ is varied to fit the observational data.

6.4. Origins of Optical Rebrightening of GRB Afterglows

Late-time observations of GRB afterglows frequently report a rebrightening in their optical-NIR light curves. For instance, Klotz et al. (2005) detected a rebrightening at $\sim 33$ min from the GRB 050515a afterglow. Using the data from Gamma-Ray burst Optical Near-infrared Detector (GROND) on board of SWIFT satellite, Nardini et al. (2011) found a fast optical rebrightening of GRB 081029 at $\sim 0.8$ hr after the burst, and Greiner et al. (2013) detected a rebrightening for GRB 100621A at $\sim 1$ hr. Moreover, Nardini et al. (2014) found the rebrightening of GRB 100814A after $\sim 0.3$ days, and Kann et al. (2018) found the rebrightening of GRB 111209A at

Figure 13. Time variation of the optical polarization of GRB afterglows (see Covino & Gotz 2016 for details) compared with our theoretical model in the $R$ band, assuming a dust cloud at 15 pc and tensile strength $S_{\text{max}} = 10^8$ erg cm$^{-3}$. The exact values of $P(t = 0)$ for various optical-NIR polarization degrees are in good agreement with our model, where the original polarization degree in the $R$ band $P(t = 0)$ is varied to fit the observational data.
can indeed reproduce the timing of optical rebrightening (see de Ugarte Postigo et al. 2018 for GRB data), assuming a dust cloud of \( A(V, t = 0) = 3 \) at 15 pc from the source and different model parameters \((S_{\text{max}}, t_0)\). The optical rebrightening time can be reproduced by the theoretical models.

Recently, de Ugarte Postigo et al. (2018) found a rapid optical rebrightening at \(\sim 2.4 \text{ hr} \) from GRB 100418A.

The nature of such an optical rebrightening is unclear. Several processes were proposed to explain this feature, including intrinsic processes related to the central engine, external shocks, and dust extinction effects (see Nardini et al. 2014 for details). To study whether our models can reproduce the optical rebrightening, in Figure 14, we plot the light curves of four GRB afterglows with an optical rebrightening (de Ugarte Postigo et al. 2018) and compare with our theoretical predictions with two model parameters \((S_{\text{max}} \text{ and } t_0)\). Our models for a dust cloud of original visual extinction \( A(V, t = 0) = 3 \) can indeed reproduce the timing of optical rebrightening; although, the models yield a lower amplitude of the rebrightening than the observations. Increasing the original extinction \( A(V, t = 0) \) can increase the rebrightening amplitude and better fit the observational data. Note that the contribution of other mechanisms (e.g., central engine and external shocks) cannot be ruled out as a cause of the optical rebrightening.

### 6.5. Effect of Light Attenuation by Intervening Dust on RATD

So far, we have considered grain rotational disruption by GRB afterglows by disregarding the effect of intervening dust. In this case, RATD can disrupt grains up to 40 pc just after about one day. In realistic situations, intervening grains will attenuate the GRB radiation, which will reduce the efficiency of RATD.

To consider the effect of light attenuation on RATD, we assume that the GRB is located at the center of a dust cloud that has a central cavity of radius of 10 pc produced by thermal sublimation (Waxman & Draine 2000) or Coulomb explosions (Fruhchter et al. 2001) during the prompt phase. We divide the intervening cloud into slices of the same thickness \( \Delta d \). Let \( \Delta \tau_\text{i}(\lambda) = A(\lambda, n) / 1.086 \) be the optical depth induced by dust grains in the \( n \)th slice with column density \( N_\text{H} = n_\text{H} \Delta d \) (see Equation (9)). The radiation energy density \( u_{\text{rad,n}} \) at the \( n \)th slice is given by

\[
u_{\text{rad,n}} = \int_{1 \text{ eV}}^{13.6 \text{ eV}} \frac{L_\lambda e^{-\tau_\text{i}(\lambda)} d\lambda}{4\pi c d^2} = \frac{L_{\text{bol}} e^{-\tau_\text{i}}}{4\pi c d^2}.
\]  

where \( L_\lambda \) is given by Equations (1) and (2), \( \tau_\text{i} \) is the effective optical depth defined as \( e^{-\tau_\text{i}} = \int L_\lambda e^{-\tau_\text{i}(\lambda)} d\lambda / L_{\text{bol}} \), and \( \tau_\text{i}(\lambda) \) is the optical depth produced by intervening dust from \( d = 10 \text{ pc} \) to the slice \( n \), which is given by

\[
\tau_\text{i}(\lambda) = \sum_{i=0}^{n-1} \Delta \tau_\text{i}(\lambda).
\]  

For a given distance \( d \), the optical depth \( \tau_\text{i}(\lambda) \) increases with the gas density \( n_\text{H} \), which results in the decrease of \( u_{\text{rad,n}} \) with \( n_\text{H} \). As a result, the active region of RATD is narrower for higher gas density \( n_\text{H} \). To demonstrate this effect, we calculate the disruption size for the various values of \( n_\text{H} \).

Figure 15 (upper panel) shows the grain disruption size as a function of cloud distances with and without radiation attenuation after one day, assuming \( S_{\text{max}} = 10^7 \text{ erg cm}^{-3} \) and
The Astrophysical Journal, 895:16 (16pp), 2020 May 20

Hoang, Chau Giang, & Tram

The parameter $R_V$ decreases with time accordingly (Figure 7). The small $R_V$ values can reproduce the steep far-UV rise extinction curves observed toward individual GRB afterglows (Schady et al. 2012). However, our present results are obtained for a single-cloud model. In realistic situations, there may be more than one cloud along the line of sight toward a GRB afterglow. The effect of multiple clouds would not change the disruption time because it is only determined by the first cloud. However, it will change the amplitude of the variation in the dust extinction and polarization.

Let $N_H$ be the total hydrogen column density along a line of sight toward a GRB afterglow. Let $f_D = N_D^H / N_H$ with $N_D^H$ being the hydrogen column density of the active region of RATD. The total extinction is then given by

$$A(\lambda) = A(\lambda)^D + A(\lambda)^{ND}$$

$$= N_H^D \left[ f_D \left( \frac{A(\lambda)}{N_H} \right)_D + (1 - f_D) \left( \frac{A(\lambda)}{N_H} \right)^{ND} \right] ,$$

where $D$ and $ND$ stand for the disruption and no-disruption regions. This corresponds to

$$\frac{A(\lambda)}{N_H} = f_D \left( \frac{A(\lambda)}{N_H} \right)_D + (1 - f_D) \left( \frac{A(\lambda)}{N_H} \right)^{ND} .$$

Since $(A(\lambda)/N_H)_{D, ND}$ only depends on the dust content of the cloud, the observed total extinction per H and $R_V$ are determined by the parameter $f_D$, i.e., the amount of dust in the closest cloud. Therefore, the observed value $R_V$ would be larger than the predicted value by the single-cloud model in Figure 7 for $f_D < 1$.

One can obtain a similar relationship for dust polarization as follows:

$$\frac{P(\lambda)}{N_H} = f_D \left( \frac{P(\lambda)}{N_H} \right)_D + (1 - f_D) \left( \frac{P(\lambda)}{N_H} \right)^{ND} .$$

Using detailed modeling of the extinction and polarization curves with observational data, we can constrain the distribution of matter along the line of sight toward GRB afterglows. This would shed light on the progenitors of GRBs.

6.7. Origins of Dark GRBs and Microwave Emission

Extinction by intervening dust grains is a popular explanation for dark optical GRBs. In light of our study, we predict that some optical GRBs may be “dark” in the beginning but become visible due to the decrease of optical/NIR extinction as a result of RATD. Time-variation monitoring of optical GRB afterglows would be useful to test this scenario. Moreover, we expect that intervening dust clouds should be far away from “dark” GRBs such that intense GRB afterglows cannot disrupt a considerable amount of dust via RATD (e.g., $d > 40$ pc).

If GRBs are indeed located in a dusty star-forming region, then, within 40 pc from GRBs, the environment is likely dominated by very small grains (VSGs) due to the RATD effect. Such tiny grains would produce significant microwave emission from 10–100 GHz via a spinning dust mechanism (Draine & Lazarian 1998; Hoang et al. 2010, 2011; Hoang & Lazarian 2016). Therefore, radio and microwave observations beyond a timescale of days would be useful to test RATD.
shedding light on the origin of dark GRBs. An unsuccessful
detection of spinning dust emission toward dark GRBs implies
that dust clouds are very far from the source.

6.8. Effects of the Grain Alignment of Extinction and
Polarization

In this paper, for modeling grain disruption by RATD, we
have assumed that grains are spin-up by RATs to a maximum
rotation rate as given by Equation (5). Such an assumption is
valid when the fraction of grains aligned with high-J attractors,
\( f_{\text{high}} \) (Hoang & Lazarian 2014), is unity. Previous studies
reveal that \( f_{\text{high}} \) essentially depends on the grain shape, grain
magnetic susceptibility, and ambient radiation field, and there
exists a faction of \( 1 - f_{\text{high}} \) aligned without high-J attractors
but only low-J attractors (Lazarian & Hoang 2007; Hoang &
Lazarian 2008). The presence of iron inclusions embedded in
dust grains is found to increase \( f_{\text{high}} \) to unity (Lazarian &
Hoang 2008; Hoang & Lazarian 2016). Moreover, in the
absence of high-J attractors (e.g., high-J repellors), grains may
still be disrupted because gas collisions randomize their
orientation in the phase space, and the grains would spend a
significant amount of time in the vicinity of high-J repellors
(Hoang & Lazarian 2008). As a result, grains can still be
disrupted if their instantaneous angular velocity exceeds \( \omega_{\text{Lar}} \).
A detailed study of grain disruption for this case should follow
the rotational dynamics of grains induced by RATs for the
GRB radiation field (e.g., Hoang & Lazarian 2016) and
compare the instantaneous centrifugal stress with the tensile
strength of the grain.

Therefore, prior to GRB afterglows, grains are already being
aligned on the high-J attractors by RATs induced by the
average interstellar radiation field (ISRF). When the GRB light
starts to shine, grains on the high-J attractor now are lifted up to
a higher angular velocity, which can be described by
Equation (5).

For modeling grain alignment by RATs, we have also
assumed that RATs induce grain alignment along the magnetic
field direction, which is usually referred to as B-RAT. Subject
to the intense radiation of GRB afterglows, the alignment axis
may change from the magnetic field (B-RAT) to the radiation
direction (i.e., k-RAT). The axis of grain alignment is with
respect to the magnetic field or radiation direction depending
on the timescales of the Larmor precession and radiation
precession (see details in Lazarian & Hoang 2007; Hoang &
Lazarian 2016; Lazarian & Hoang 2019).

A grain spinning at angular velocity \( \omega \), the radiation
precession time is defined as

\[
\tau_{\text{rad}} = \frac{2\pi L_{\text{rad}}}{\omega},
\]

which increases with \( \omega \), i.e., faster rotating grains have slower
precession. Note that previous studies estimate the radiation
precession time at grain thermal angular velocity, i.e., \( \omega = \omega_{T} \)
(e.g., Lazarian & Hoang 2019). However, for our situation,
prior to the GRB afterglow, grains are already aligned with the
magnetic field at the high-J attractor due to the averaged
interstellar radiation field of the local galaxy (ISRF). Therefore,
\( \tau_{\text{rad}} \) should be evaluated at the angular momentum of the high-J
attractor, denoted by \( \omega_{\text{ISRF}} \).

Silicate grains of ordinary paramagnetic material with
magnetic susceptibility \( \chi_{p}(0) \) are magnetized due to spinning
via the Barnett effect. The resulting magnetic moment experiences Larmor precession around the ambient magnetic
field (Hoang & Lazarian 2016; Lazarian & Hoang 2019).

The instantaneous magnetic moment due to the Barnett
effect is equal to

\[
\mu_{\text{Batt}} = \frac{\chi(0) \omega}{\gamma_{g}} V = -\frac{\chi(0) \delta V}{g_e \mu_p} \omega,
\]

where \( \gamma_{g} = -e_{g} \mu_{B} / h \approx -e / (m_e c) \) is the gyromagnetic ratio
of an electron, \( g_e \approx 2 \) is the \( g \)– factor, and \( \mu_{p} = e / 2m_e c \approx 9.26 \times 10^{-21} \text{erg G}^{-1} \) is the Bohr magneton
(Dolginov & Mitrofanov 1976). Here \( \chi(0) \sim 0.03 \mu_p (20/\nu_{\text{GRB}}) \),
with \( \nu_{\text{GRB}} \sim 0.1 \) the fraction of paramagnetic atoms in the dust
grain, is the magnetic susceptibility of ordinary paramagnetic
material (Hoang & Lazarian 2016).

The Larmor precession time is given by (see Hoang &
Lazarian 2016)

\[
\tau_{\text{Lar}} = \frac{2\pi L_{\text{rad}}}{\omega_{\text{ISRF}}} \approx 0.065 \frac{a_{-5}^{2} \nu_{0.1}^{3}}{B} \left( \frac{10^{-3}}{\chi(0)} \right) \left( \frac{10 \mu_{G}}{B} \right) \text{yr.}
\]

To see if grains can be aligned via k-RAT versus B-RAT, let
us compare the ratio

\[
\frac{\tau_{\text{rad}}}{\tau_{\text{Lar}}} \sim \left( \frac{0.15}{a_{-5}} \right) \left( \frac{10^{5}}{U} \right) \left( \frac{\chi(0)}{10^{-3}} \right) \left( \frac{B}{5 \mu_{G}} \right) \left( \frac{\omega_{\text{ISRF}}}{100} \right),
\]

where \( \omega_{\text{ISRF}} = \omega_{\text{ISRF}} / \omega_{T} \), and their typical value for the ISRF
of \( \omega_{\text{ISRF}} \sim 100 \) is taken for grains of \( a \sim 0.1 \) \( \mu \text{m} \) (see Hoang &
Lazarian 2009).

For grains with iron inclusions with \( N_{\text{cl}} \) iron atoms per
cluster, the magnetic susceptibility is enhanced to \( \chi_{\text{sp}} \sim N_{\text{cl}} \chi(0) \) (Hoang & Lazarian 2016). Equation (27) is rewritten as

\[
\frac{\tau_{\text{rad}}}{\tau_{\text{Lar}}} \sim \left( \frac{0.3}{a_{-5}} \right) \left( \frac{10^{11}}{U} \right) \left( \frac{N_{\text{cl}}}{100} \right) \left( \frac{B}{100 \mu_{G}} \right) \left( \frac{\omega_{\text{ISRF}}}{100} \right).
\]

The radiation strength of GRB afterglows, \( U \), decreases over
time, from an initial value of \( U \sim 10^{14} \) at \( t_{0} \sim 10 \) to \( U \sim 10^{8} \)
at \( t \sim 10^{3} \) s, assuming \( d \sim 10 \) pc (see Equation (1)). Assuming
\( N_{\text{cl}} \sim 10^{3} \), the magnetic field required for the B-RAT alignment
is \( B \gtrsim 0.3-300 \mu \text{G} \) during the early time \( t < 10^{3} \) s. As
the time increases, the radiation strength decreases as given by
Equation (1), and grains are aligned with the magnetic field.

Note that, for ordinary paramagnetic grains or diamagnetic
carbonaceous grains, the axis of alignment is the radiation
direction because \( \tau_{\text{rad}} \ll \tau_{\text{Lar}} \). The \( k \)-RAT alignment corre-
sponds to the short axis parallel to the GRB light, which does
not produce the polarization of its own light.

7. Summary

We studied the rotational disruption of dust grains in the
local environments of GRB afterglows using the Radiative
Torque Disruption (RATD) mechanism and the model
extinction and polarization of GRB afterglows. Our main
findings are summarized as follows:

1. For an optically thin medium, we show that large dust
grains can be disrupted into smaller ones within one day
up to 40 pc due to RATD. While thermal sublimation and
Coulomb explosions only occur during the prompt phase
of 10 s, RATD can disrupt grains by GRB afterglows at $t > 10$ s.

2. We calculate the time-varying dust extinction of GRB afterglows in the presence of RATD. We find that the optical-NIR extinction decreases, whereas the UV and FUV extinction increase gradually until a day after the burst due to the enhancement of small grains by RATD. This causes the time variability of color excess $E(B - V)$.

3. We model the polarization of GRB afterglows due to differential extinction by aligned grains. We show that the optical-IR polarization first increases with time due to enhanced alignment by strong radiation fields and then decreases rapidly when grain disruption by RATD begins.

4. We compare our theoretical predictions with observational properties of GRB afterglows. We find that our predictions are, in general, supported by observations, including SMC-like extinction curves and low values of $R_V$ of GRB afterglows. Grain disruption by RATD can partly contribute to the optical rebrightening of GRB afterglows at late times.

5. The rotational disruption of large grains by GRB afterglows increases the abundance of very small grains in the local environment around GRBs. We suggest observing microwave emission from spinning dust toward GRB afterglows as a new way to test RATD and the origin of dark GRBs.

We are grateful to the referee for insightful comments that improved our manuscript. We thank E. Troja for discussions during the early stage of this work. This research was supported by the National Research Foundation of Korea (NRF) grants funded by the Korea government (MSIT) through the Basic Science Research Program (2017R1D1A1B03035359) and Mid-career Research Program (2019R1A2C1087045).

ORCID iDs

Thiem Hoang © https://orcid.org/0000-0003-2017-0982
Le Ngoc Tram © https://orcid.org/0000-0002-6488-8227

References

Abbás, M. M., Craven, P. D., Spann, J. F., et al. 2004, ApJ, 614, 781
Andersson, B.-G., Lazarian, A., & Viallancourt, J. E. 2015, ARA&A, 53, 501
Barth, A. J., Sari, R., Cohen, M. H., et al. 2003, ApJL, 584, L47
Berger, E., Kulkarni, S. R., Pooley, G., et al. 2003, ApJ, 584, L47
Bolmer, J., Greiner, J., Krühler, T., et al. 2018, A&A, 609, A62
Burke, J. R., & Silk, J. 1974, ApJ, 190, 1
Chiar, J. E., Adamson, A. J., Whittet, D. C. B., et al. 2006, ApJ, 651, 268
Covino, S., & Gotz, D. 2016, A&AT, 29, 205
Covino, S., & Gotz, D. 2016, A&A, 589, L3
Covino, S., Malesani, D., Ghisellini, G., et al. 2003a, A&A, 400, L9
De Ugarte Postigo, A., Thöne, C. C., Bensch, K., et al. 2018, A&A, 620, A190
Dolginov, A. Z., & Mitrofanov, I. G. 1976, ApSS, 43, 291
Draine, B. T., & Hao, L. 2002, ApJ, 569, 780
Draine, B. T., & Lazarian, A. 1998, ApJ, 508, 157
Draine, B. T., & Li, A. 2007, ApJ, 657, 810
Draine, B. T., & Salpeter, E. E. 1979, ApJ, 231, 77
Draine, B. T., & Weingartner, J. C. 1996, ApJ, 470, 551
Fraija, N., Dichiara, S., de O S Pedroreira, A. C. C., et al. 2019, ApJL, 879, 26
Fruchter, A., Krollik, J. H., & Rhoads, J. E. 2001, ApJ, 563, 597
Gehrels, N., Ramirez-Ruiz, E., & Fox, D. B. 2009, ARA&A, 47, 567
Giang, N. C., Hoang, T., & Tram, L. N. 2020, ApJ, 888, 93
Greiner, J., Krühler, T., Nardini, M., et al. 2013, A&A, 560, A70
Heintz, K. E., Fynbo, J. P. U., Jakobsson, P., et al. 2017, A&A, 601, A83
Herrnen, J., Lazarian, A., & Hoang, T. 2019, ApJ, 878, 96
Hoang, T. 2017, ApJ, 836, 13
Hoang, T. 2019, ApJL, 876, 13
Hoang, T., Draine, B. T., & Lazarian, A. 2010, ApJ, 715, 1462
Hoang, T., & Lazarian, A. 2008, MNRAS, 388, 117
Hoang, T., & Lazarian, A. 2009, ApJ, 695, 1457
Hoang, T., & Lazarian, A. 2008, ApJL, 697, L316
Hoang, T., & Lazarian, A. 2014, MNRAS, 438, 680
Hoang, T., & Lazarian, A. 2016, ApJ, 831, 159
Hoang, T., Lazarian, A., & Andersson, B.-G. 2015a, MNRAS, 448, 1178
Hoang, T., Lazarian, A., & Draine, B. T. 2011, ApJ, 741, 87
Hoang, T., Lazarian, A., & Martin, P. G. 2013, ApJ, 779, 152
Hoang, T., Lazarian, A., & Schlickeiser, R. 2015b, ApJ, 806, 255
Hoang, T., Tram, L. N., Lee, H., & Ahn, S.-H. 2019, NatAs, 3, 766
Kann, D. A., Schady, P., Olivares, E. F., et al. 2018, A&A, 617, A122
Klotz, A., Boër, M., Atteia, J. L., et al. 2005, A&A, 439, L35
Laskar, T., Alexander, K. D., Gill, R., et al. 2019, ApJ, 878, 26
Lazarian, A., Andersson, B.-G., & Hoang, T. 2015, in Polarisometry of Stars and Planetary Systems, ed. L. Kolokolova, J. Hough, & A.-C. Levasseur-Regourd (Cambridge: Cambridge Univ. Press), 81
Lazarian, A., & Hoang, T. 2007, MNRAS, 378, 910
Lazarian, A., & Hoang, T. 2008, ApJL, 676, L25
Lazarian, A., & Hoang, T. 2019, ApJ, 883, 122
Mathis, J. S. 1986, ApJ, 308, 281
Mathis, J. S., Mezger, P. G., & Panagia, N. 1983, A&A, 500, 259
Mathis, J. S., Rumpl, W., & Nordsieck, K. H. 1977, ApJ, 217, 425
Melandri, A., Covino, S., Zaninoni, E., et al. 2017, A&A, 607, A29
Meszaros, P., & Rees, M. J. 1997, ApJ, 476, 232
Morgan, A. N., Perley, D. A., Cenko, S. B., et al. 2014, MNRAS, 440, 1810
Nardini, M., Elliott, J., Filgas, R., et al. 2014, A&A, 562, A29
Nardini, M., Greiner, J., Krühler, T., et al. 2011, A&A, 531, A39
Paczyński, B. 1998, ApJL, 494, L45
Perley, D. A., Bloom, J. S., Klein, C. R., et al. 2010, MNRAS, 406, 2473
Perna, R., & Lazatti, D. 2002, ApJ, 580, 261
Perna, R., Lazatti, D., & Fiore, F. 2003, ApJ, 585, 775
Rol, E., Wijers, R. A. M. J., Vreeswijk, P. E., et al. 2000, ApJ, 540, 707
Schady, P. 2017, RSOS, 4, 170304
Schady, P., Dwyer, T., Page, M. J., et al. 2012, A&A, 537, 15
Schady, P., Page, M. J., Oates, S. R., et al. 2010, MNRAS, 401, 2773
Stratta, G., Gendre, B., Atteia, J. L., et al. 2013, ApJ, 779, 66
Waxman, E., & Draine, B. T. 2000, ApJ, 537, 796
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296
Weingartner, J. C., Draine, B. T., & Barr, D. K. 2006, ApJ, 645, 1188
Zafar, T., Heintz, K. E., Karakas, A., et al. 2019, MNRAS, 490, 2599
Zafar, T., Watson, D., Molter, P., et al. 2018, MNRAS, 479, 1542